BRL-SP-92

SPECIAL PUBLICATIONS BRL-SP-92

BRL

ELECTROTHERMAL-CHEMICAL MODELING AND DIAGNOSTICS WORKSHOP, VOLUME 2

GLORIA P. WREN
SHARON L. RICHARDSON

OCTOBER 1991

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

UNCLASSIFIED

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1991	Final, 9–11 Jul 91

4. TITLE AND SUBTITLE

Electrothermal-Chemical Modeling and Diagnostics Workshop, Vol. 2

5. FUNDING NUMBERS

1F2Z9W9XDGS3
DA31 1880

6. AUTHOR(S)

Gloria P. Wren and Sharon L. Richardson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

BRL-SP-92

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report contains the abstracts and viewgraphs of the papers presented at the JANNAF workshop on Electrothermal-Chemical Modeling and Diagnostics, 9–11 July 1991, held at the U.S. Army Ballistic Research Laboratory.

14. SUBJECT TERMS

electrothermal-chemical; ETC; electrothermal gun; electric guns; interior ballistics

15. NUMBER OF PAGES

407

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

		Page
	ACKNOWLEDGMENTS	v
1.	INTRODUCTION	1
2.	ELECTROTHERMAL-CHEMICAL GUN PROGRAM (D. A. Benson, P. Cahill, S. N. Kempka, and R. L. Woodfin, Sandia National Laboratories)	3
3.	DIAGNOSTICS DEVELOPMENT FOR THE ETC PROGRAM (D. W. Sweeney, S. Vosen, J. Gray, and R. Armstrong, Sandia National Laboratories)	35
4.	DEVELOPMENT OF AN UPWIND/IMPLICIT COMPUTATIONAL MODEL FOR THE ADVANCEMENT OF ARMY ETC GUNS (N. Sinha, A. Hosangadi, and S. N. Dash, Science Applications International Corporation)	65
5.	RECENT ADVANCES IN CAP_{tm} GUN MODELING (D. Cook and J. Dyvik, FMC Corporation)	101
6.	30-MM ETC BALLISTIC DIAGNOSTIC FACILITY (K. White, I. Stobie, B. Bensinger, S. Driesen, H. Burden, G. Katulka, and A. Juhasz, BRL)	121
7.	NUMERCIAL SIMULATION OF THE INTERIOR BALLISTIC PROCESSES IN AN ETC GUN (J. L. Chen, F. B. Cheung, and K. K. Kuo, Pennsylvania State University)	143
8.	FINITE-ELEMENT MODELING OF ELECTROTHERMAL-CHEMICAL GUNS (N. K. Winsor and S. A. Goldsten, GT-Devices, Inc.)	177
9.	SPECIAL DIAGNOSTICS AND INSTRUMENTATION (R. D. Richardson and M. D. Haworth, Science Applications International Corporation)	207
10.	FIRST PRINCIPLES MODELING OF A DNA 60-MM ETC GUN DESIGN (C. C. Hsiao, G. T. Phillips, and F. Y. Su, Science Applications International Corporation)	235
11.	PHYSICS OF ETC PLASMA-FLUID INTERACTIONS (B. A. Kashiwa, H. A. Davis, and R. J. Trainor, Jr., Los Alamos National Laboratory)	267
12.	OBSERVATIONS AND MODELING OF FUNDAMENTAL ELECTROTHERMAL GUN PHENOMENA (H. A. Davis, R. R. Bartsch, B. A. Kashiwa, and N. T. Padial, Los Alamos National Laboratory)	277

Page

13. ELECTROTHERMAL-CHEMICAL GUN MODELING (D. W. King and Hugh McElroy, Olin Corporation) 313

14. RAILGUN RESEARCH RELEVANT TO ELECTROTHERMAL GUNS (J. H. Batteh, Science Applications International Corporation) 327

15. IN-BORE POSITION AND VELOCITY MEASUREMENT TECHNIQUES (R. Bartsch and H. A. Davis, Los Alamos National Laboratory) 347

16. IN-BORE ACCELERATION MEASUREMENTS WITH AN INSTRUMENTED RAILGUN PROJECTILE (D. M. Littrell, K. A. Jamison, G. E. Rolader, U. S. Air Force Armament Directorate) 367

APPENDIX A: FINAL AGENDAS 397

APPENDIX B: ATTENDEES 403

DISTRIBUTION LIST 409

ACKNOWLEDGMENTS

I would like to take this public opportunity to thank each of the workshop participants for their excellent presentations. The support of government, university, contractors, and industry is gratefully acknowledged. Sincere appreciation is expressed to Mrs. Sharon Richardson, Workshop Coordinator, and Ms. Jennifer Hughey, student contractor, for their invaluable assistance.

INTENTIONALLY LEFT BLANK.

1. INTRODUCTION

Currently, a number of diverse efforts are underway toward modeling and diagnostics of the electrothermal-chemical (ETC) gun. These efforts have been initiated primarily in the past two years, include Government (Army, Navy, DNA, and DOE), university, and industry, and are funded by both private and Government sectors.

The three (Army, Navy, and DNA) major Government programs associated with development of ETC technology have target dates of FY92 for assessment. Thus, a need exists to increase and encourage progress toward understanding the dominant physical mechanisms in the ETC gun, which hopefully, will result in improved control of the interior ballistic process.

As a means of addressing the above concerns, a JANNAF workshop on Electrothermal-Chemical Modeling and Diagnostics was held July 9–11, 1991, at the U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD. The objectives of the workshop were to assemble experts, drawn from gun, plasma physics, engineering, and related disciplines from Government, industry, and academia to examine theoretical methodologies and experimental approaches and data, and to review and evaluate the present state-of-knowledge in the ETC gun. Specifically, the workshop objectives were to:

- Survey methods of modeling interior ballistic process, particularly the interaction of the plasma and the work fluid.

- Summarize the areas of agreement and determine diagnostic experiments needed to validate hypotheses and provide input for models.

- Identify diagnostic experiments which may impact modeling.

- Assess the state of plasma modeling and diagnostics for ETC guns.

- Identify gaps in experimental and theoretical investigations.

- Recommend future ETC gun research areas.

Workshop participants jointly summarized current modeling and diagnostic efforts in the U.S. and experimental measurements needed to improve ETC models. Their summary is in the form of the following charts (see vol. 1):

a. Current ETC Modeling Activities in the U.S.

b. Diagnostic Measurements Desired by ETC Modelers

c. Current ETC Diagnostic Activities in the U.S.

d. Use of Diagnostic Measurements Desired by ETC Modelers

The dialogue between modelers and experimentalists will, hopefully, provide a common focus for future work.

ELECTROTHERMAL-CHEMICAL GUN PROGRAM

D. A. Benson, P. Cahill, S. N. Kempka, and R. L. Woodfin
Sandia National Laboratories
Albuquerque, NM 87185-5800

ABSTRACT

The Sandia National Laboratories ETC Gun Program seeks to achieve a better understanding of the fundamental processes at work in such a device. An experimental apparatus resembling a gun chamber with an external "capillary" for the generation of a plasma which mixes with a working fluid in the chamber has been constructed. A series of detailed models of the process is being developed. Several diagnostics techniques are being developed to better measure the parameters of the process. Several possible fuel materials, are being investigated. Future plans include a more "gun-like" apparatus with variable geometries.

Electrothermal-Chemical Gun Program

Dr. Ronald L. Woodfin
Advanced Projects Division V
(505) 844-3111 AV 244-3111

Project Organization

Sponsors:

DoE

Office of Munitions

ARDEC - Electric Armaments Division

Technical Coordinator:

BRL - Advanced Ballistic Concepts

Sandia:

Albuquerque, NM - Plasma/Accumulator Exp's & Models
Materials Studies, Project Management

Livermore, CA - Shock Tube Ablation Exp's & Models
Mixing & Combustion Diagnostics Dev

Critical Needs & Major Unknowns
(BRL 1989)

Critical needs:

- *New working fluids
- *Well instrumented firings
- *Plasma / working fluid diagnostics
- Bore temperature and erosion studies
- Projections of growth of power supplies

Major unknowns:

- *Physics & chemistry of mixing
- *Gas generation rate *vs* electrical input
- *Gun thermal environment
- Heat transfer & erosion
- Muzzle reactions & weapon effluents
- Ballistic temperature coefficient
- *Reproducibility

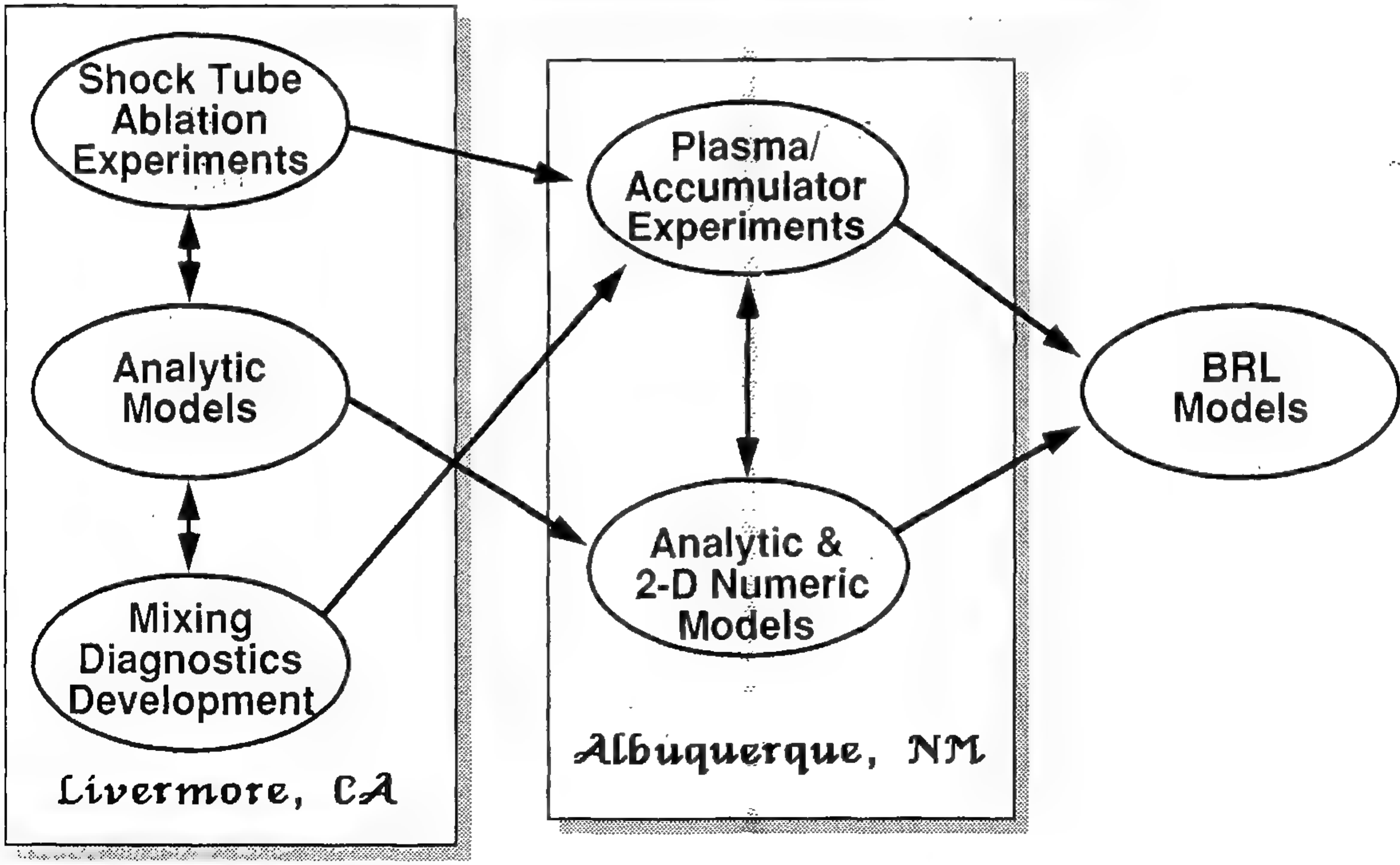
Scope & Target

- Physics of plasma arc sources
- Physics & chemistry of mixing processes
- Modeling of the electric / thermal / chemical process
- Properties of propellant materials
- Gun chamber diagnostics
- Improvements in plasma density / mixing

Project Character

- Integrated experimental & analytical effort
- Produces & verifies detailed physical models
- Supports Army modeling of interior ballistics
- Develops new diagnostics for mixing & combustion

Program Structure



Required Diagnostic Capability

Goal is to be able to identify:

plasma penetration depth & volume

&

location of species

under gun conditions

as a function of time.

Diagnostics will measure:

Plasma development

Temperature

Species

Physics of Plasma Arc Sources

11

- Experimental chamber
  - To 100,000 psi
  - 40KJ
  - Heavily instrumented
  - Contained products
  - Ablative capillary liner
- Analytical model
  - 2-D, axisymmetric, compressible flow
  - Dissociated & ionized species
  - Electrical conductivity
  - Gas equation of state
  - Radiative energy transport by diffusion approximation

Physics & Chemistry of the Mixing Process

Plasma / working fluid interaction

- Flow
- Mixing
- Areas of reactivity
- Entrainment processes

Ablation of capillary material

- Mass / momentum addition to plasma
- Reactivity alteration in accumulator

Constitution of plasma

- Mixture of ablative material & working fluid

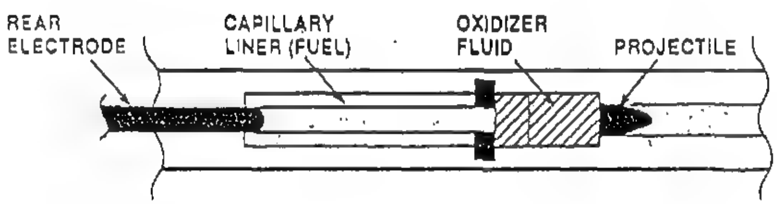
Electrothermal Injector Studies

Develop ETC technology base for future system assessment

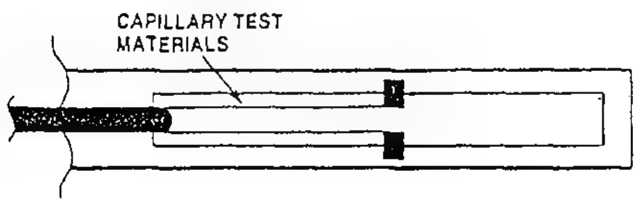
- Fundamental electrothermal chemical measurements
- Materials development
- Modeling
- Coordinate with DoD and industry efforts

13

SIMPLIFIED GUN DESIGN



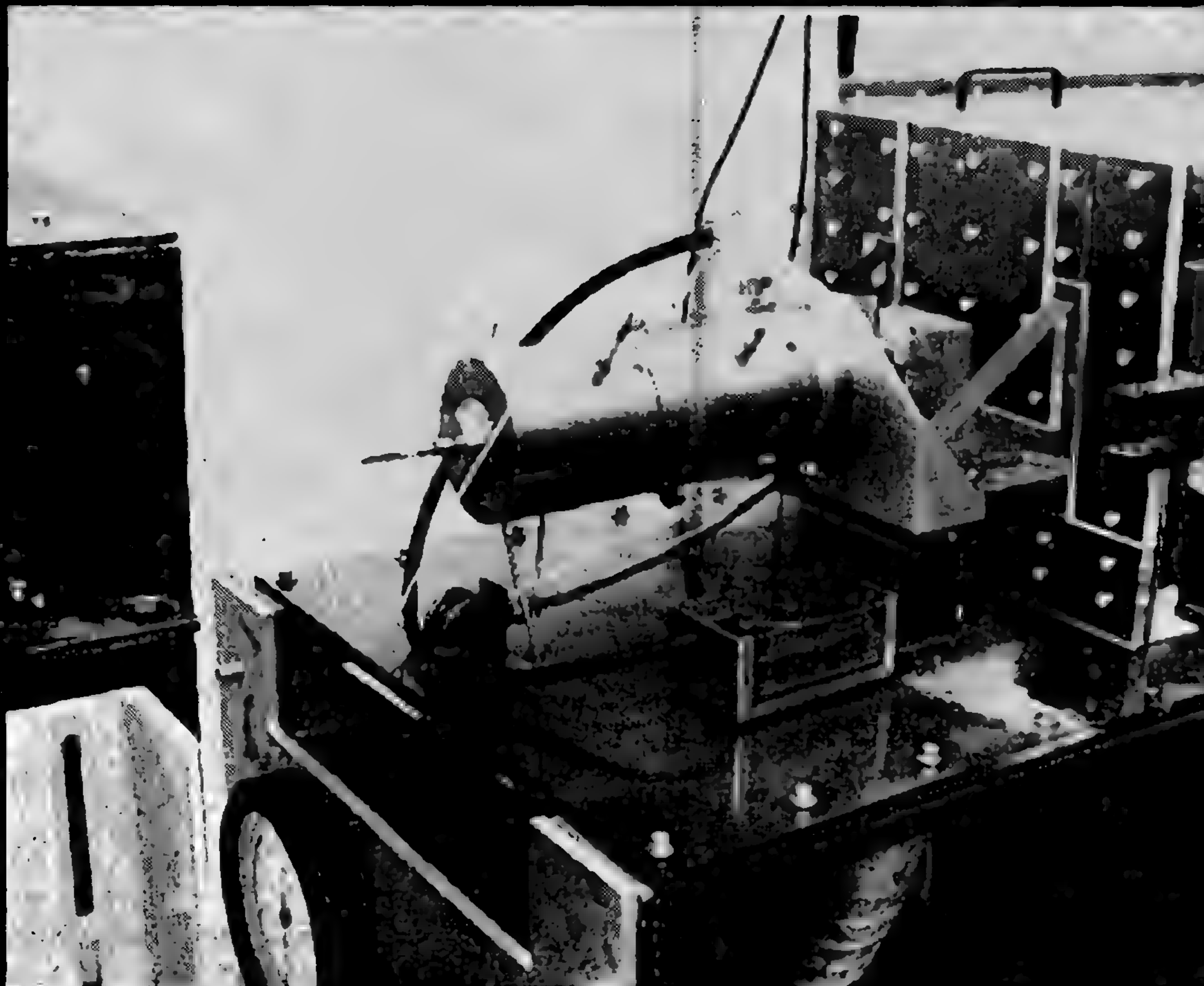
ELECTROTHERMAL INJECTOR TEST



Objectives

- Develop closed vessel electrothermal test
- Acquire data for capillary model development
- Improve efficiency and controllability of ETC devices
- Enhance capillary mass transfer
- Evaluate reactive materials for use in capillary
- Study capillary turbulence, heat transfer, erosion

Electrothermal Injector Mounted on Capacitor Bank



15

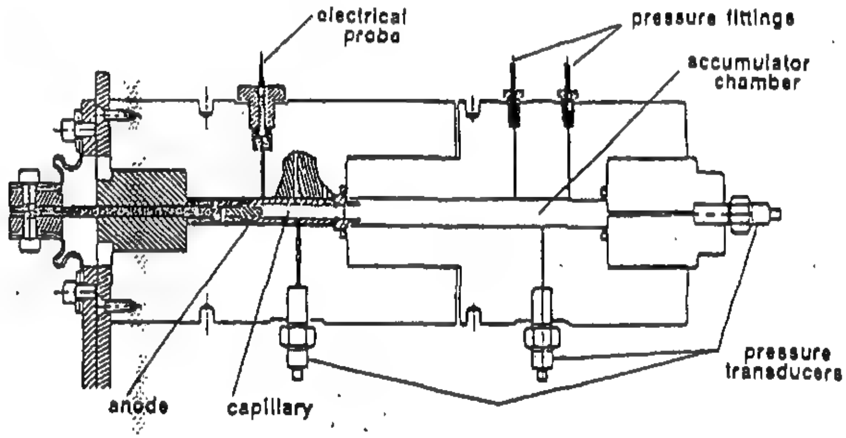
Electrothermal Injector Experimental Apparatus

- Capacitor Discharge System
  40 kJ, 250 kA, 10 kV

- Liner Materials
  Polyethylene
  Delrin
  Nitrated Polyethylene

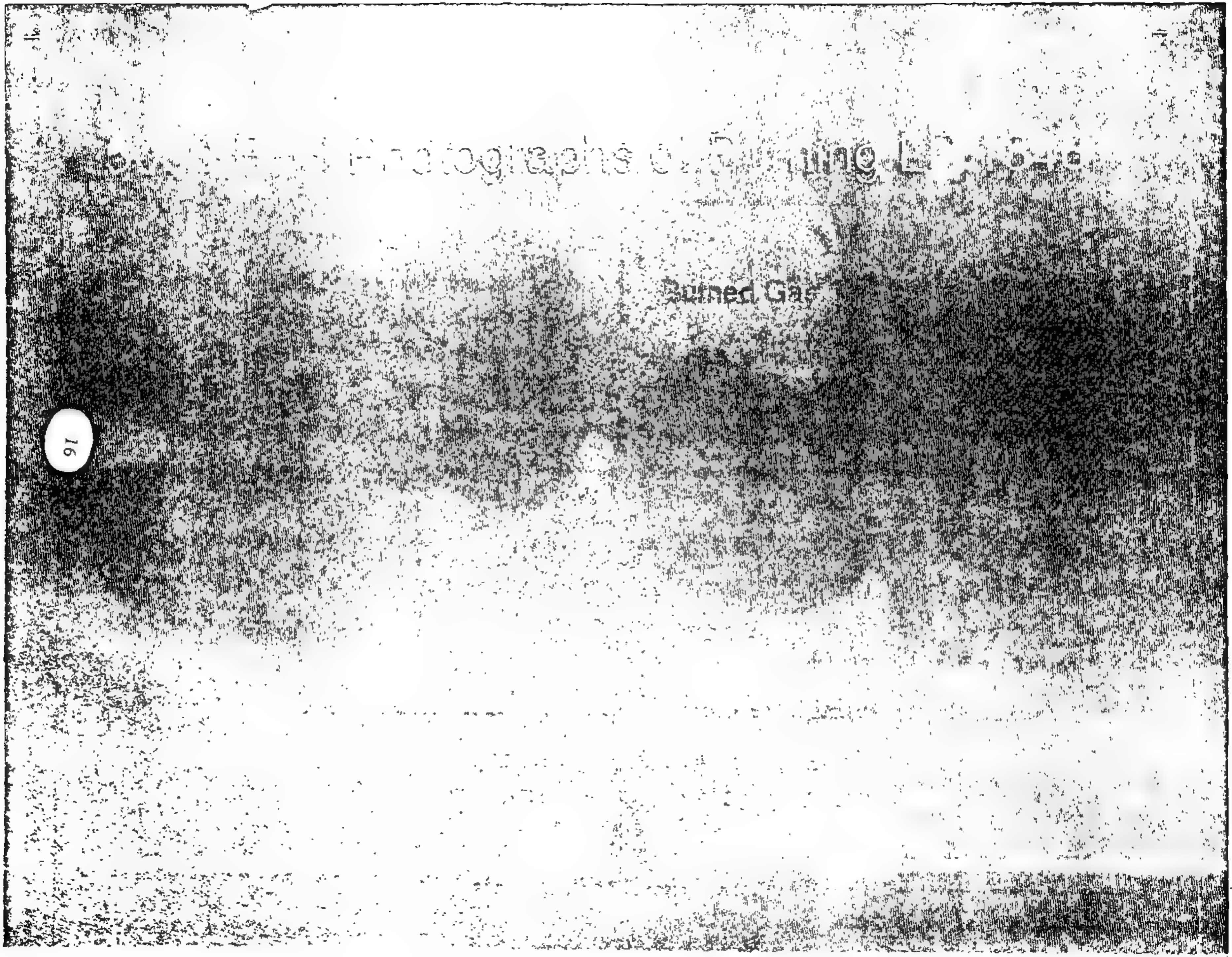
- Diagnostics
  Arc Impedance
  Electrical Power Input
  Accumulator Chamber Pressure
  Capillary Pressure vs Time
  Total Mass Removal from Capillary Liner

- Post-Test Particulate Analysis
  Scanning Electron Microscopy
  Energy Dispersive X-Ray Analysis

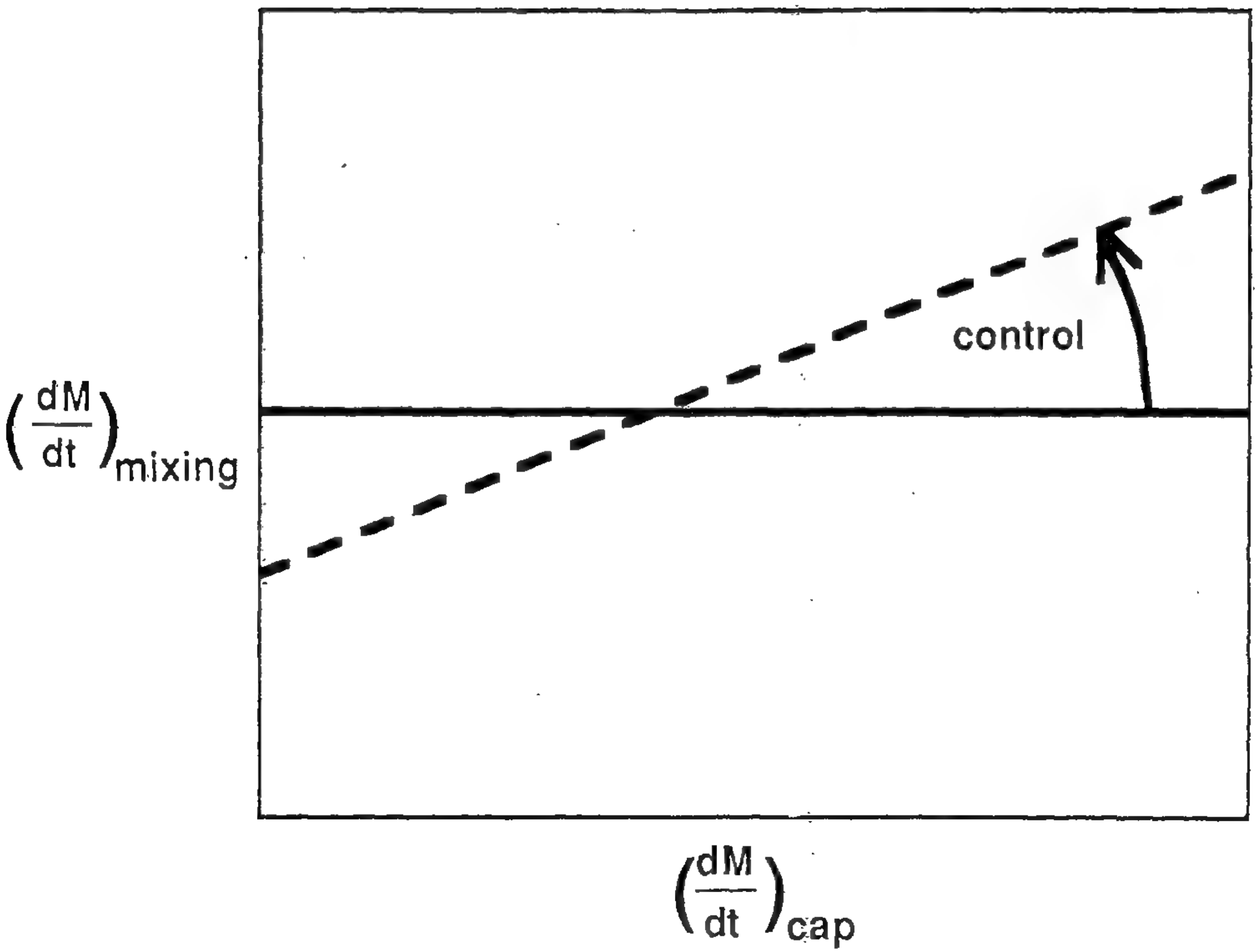


Electrothermal Injector Cross-Section View

- Experimental Setup
  Accumulator Volume 14 cm^3
  Arc Length 4.3 cm
  Capillary Inside Dia. 0.58 cm
  Max. Pressure 100 kpsi


Photographs
Burned Gas

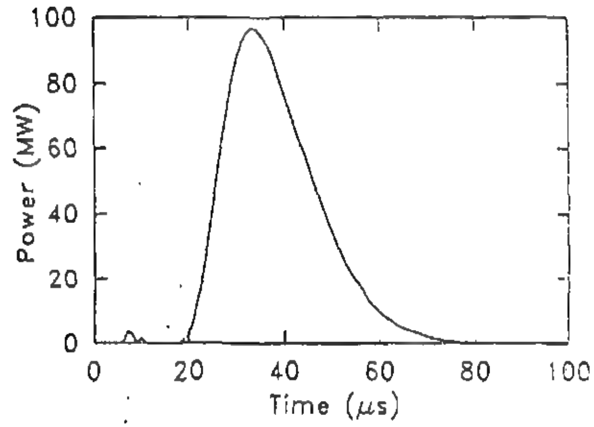
Effect of Capillary Efflux on Accumulator Mixing

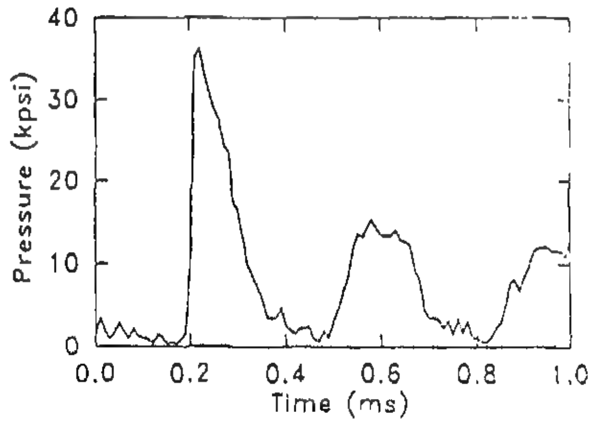


Accomplishments on Electrothermal Injector Project

- Developed closed vessel test system for the Dynamic Heating Facility
- Conducted initial tests with polyethylene (10 to 80 mg ablated)
- Calculated optical absorption to predict radiative paths under ET conditions
- Performed hydrodynamic calculations to show characteristic times for capillary
- Prepared and characterized nitrated polyethylene materials (PEVN) for liners
- Demonstrated enhanced arc induced ablation with PEVN liners

arc power dissipated





accumulator chamber pressure

Modeling of Thermal / Electric / Chemical Process

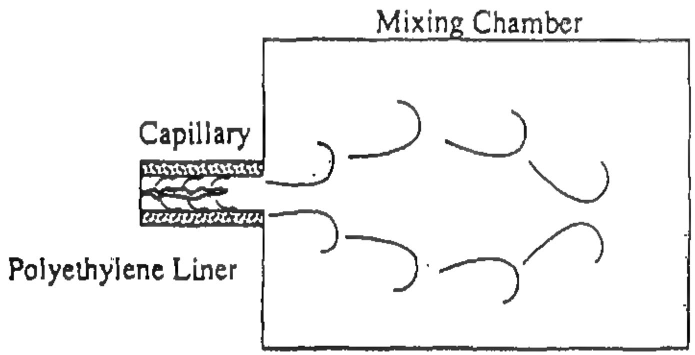
Model of injector / accumulator

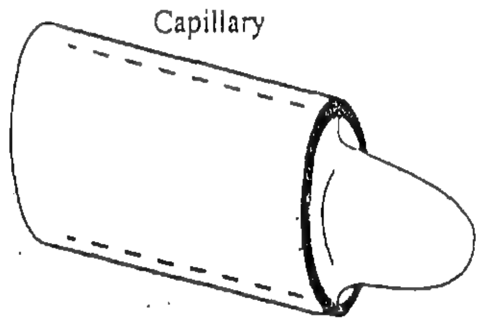
- Electric discharge
- Plasma generation
- 2-D fluid flow
- Adaptation of existing codes
- Mixing, combustion, heat transfer
- Geometric sensitivity studies

Model of ablation process

- Code models measurements
- Input to 2-D model

1-D Radial Model of an ETC Capillary





- Objectives

1. Examine extent of radial variations in plasma

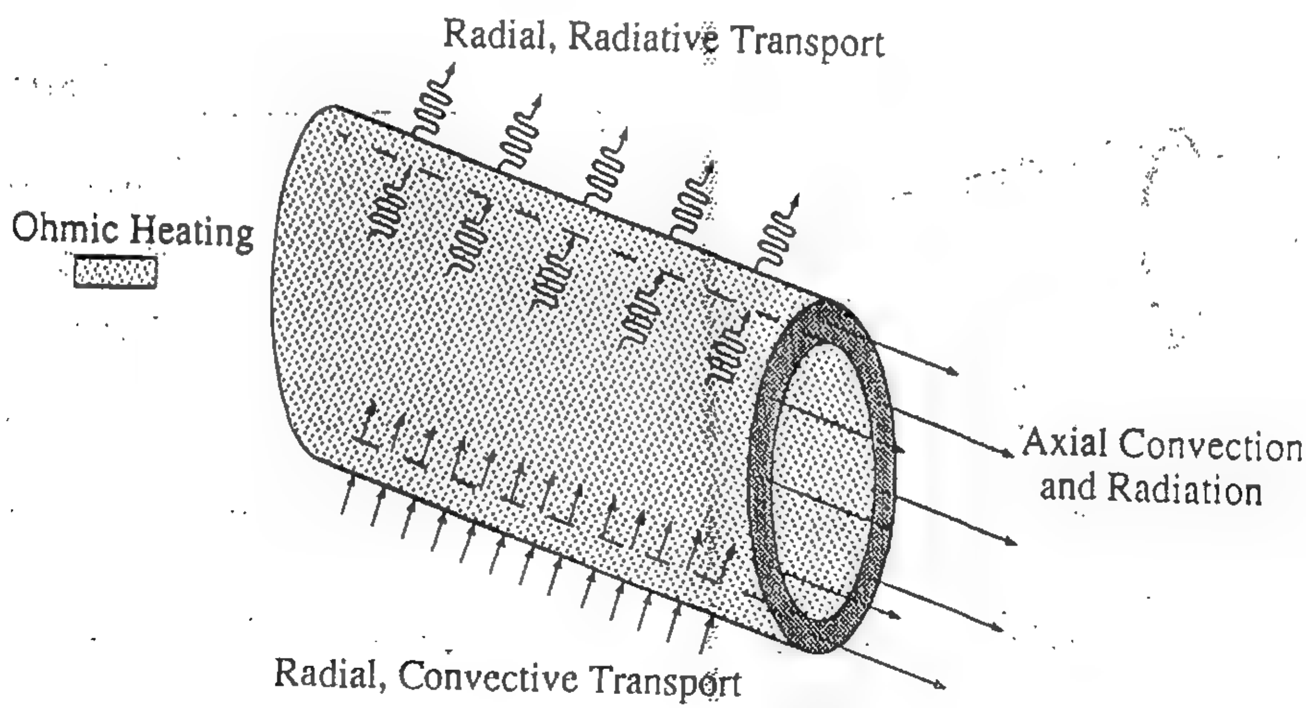
   - radial variations influence mixing instabilities

2. Validate plasma transport properties for use in 2-D hydro model

   - diffusive radiation transport (Rosseland mean free path)

   - electrical conductivity (electron-ion, electron-neutral collisions)

Energy Balance on Differential Annulus



21

Assumptions in 1-D Radial Model

22

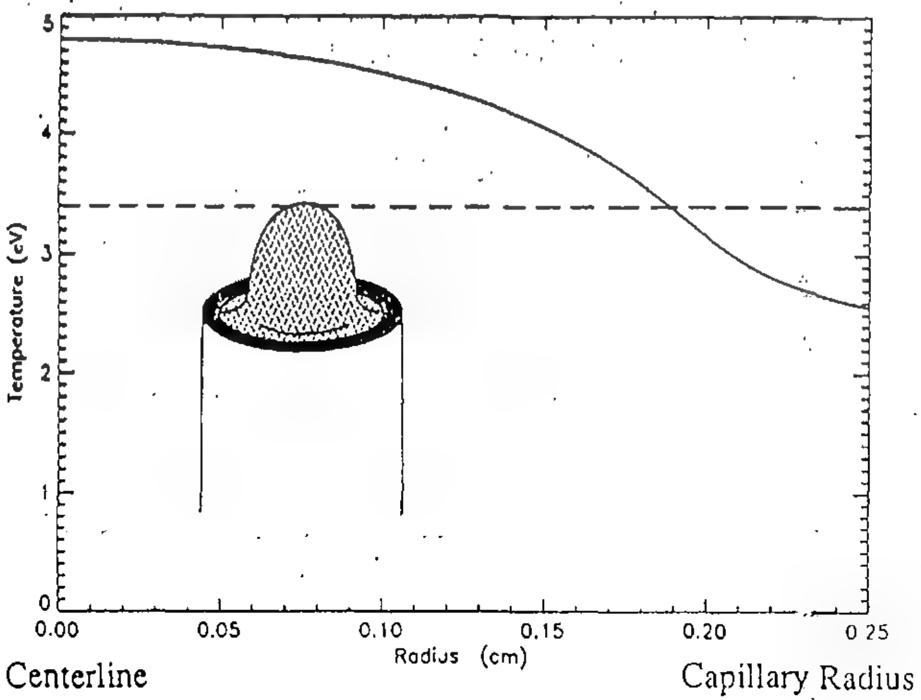
- Steady-State, LTE, (collision rate)$^{-1}$ << τ_{sonic}
- Axially uniform velocity and temperature
- Axial flow: Exit capillary at local sonic velocity
- Radial flow: obtained from conservation of mass
- Radial pressure gradient from radial momentum equation (mhd included)

$$\rho v_r \frac{d}{dr}(v_r) = -\frac{dP}{dr}$$

- Uniform Electrical field
- Saha equations: C, C^+, C^{++}, H, H^+

Computed Radial Distributions

- Find solution that matches SNL experimental data
  - Peak values: 40 kAmps, 100 MW, 600 V/cm
- Temperature varies from 4.8 eV to 2.5 eV across capillary radius (0.25 cm)



- Species also vary significantly with radius
- Uniform temperature:
  - Power = $\sigma T^4 \cdot 2\pi RL$

1-D Radial Model Conclusions

- Radial model provides insight into capillary physics:
  - Radial variations in plasma temperature, species are large
  - Radial variations effect mixing instabilities, control issue
- Modeling issues to be resolved:
  - Ionization energy depends on density (constant value used)
  - Electrical conductivity of plasma for high densities

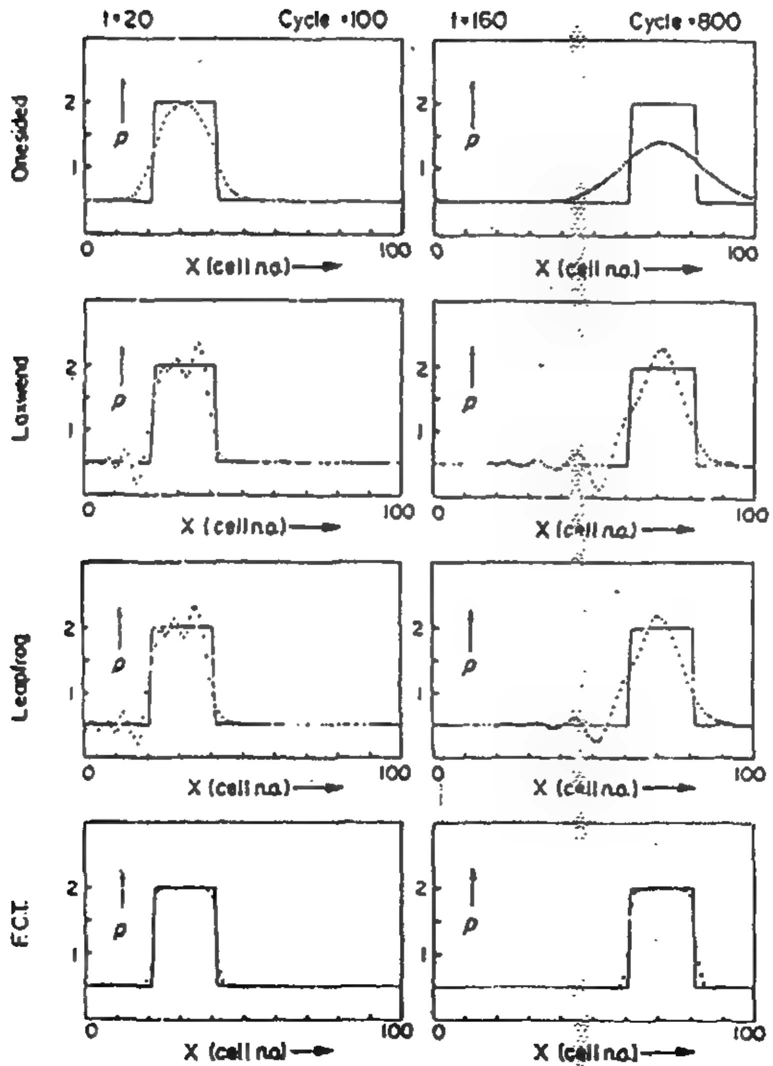
24

2-D Hydrodynamic Model

- Include capillary model in 2-D hydro model to examine scaling, mixing
- Time-step issue
  - Explicit: expensive, accurate
  - Implicit: cheaper, large numerical diffusion, dispersion
- Explicit: time-split diffusive and convective transport: different time scales
- Flux Corrected Transport for convective transport
- Test: Numerical Simulation of Convection: Propagating Wave

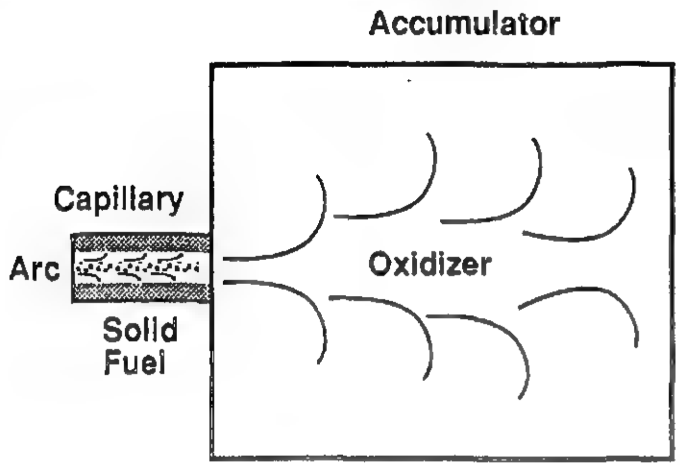
$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} = 0$$

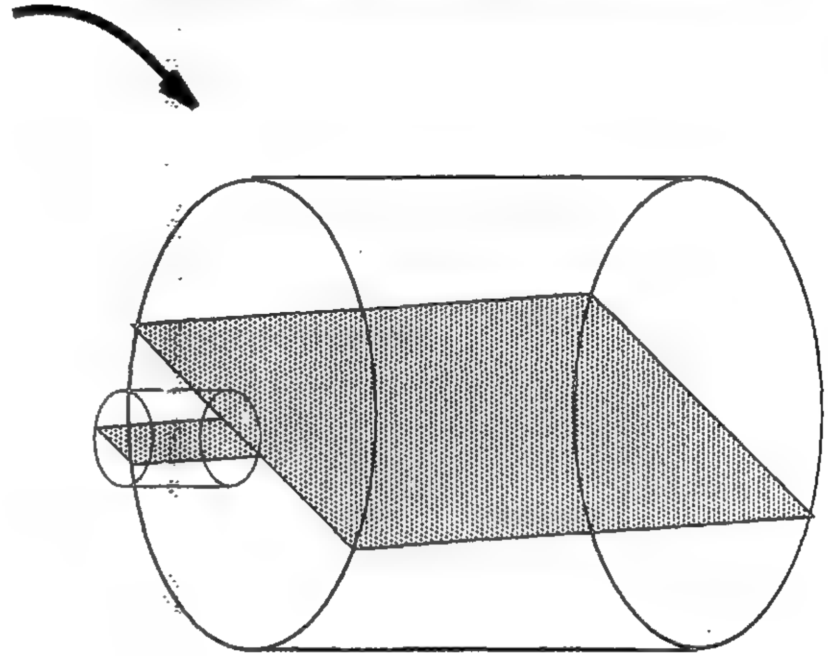
Propagating Square Wave

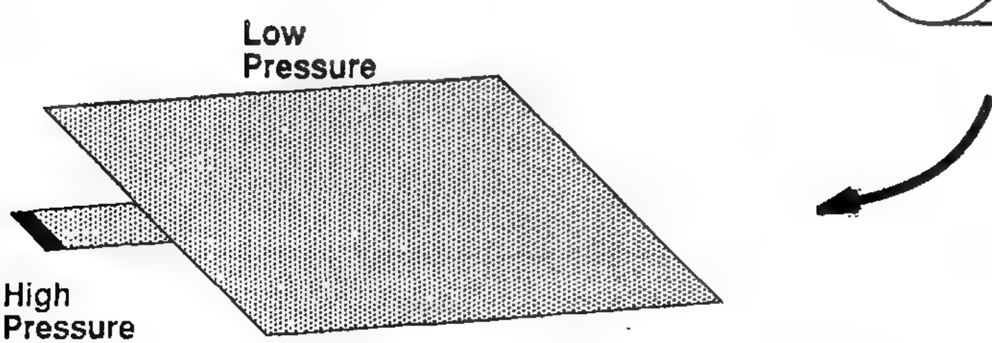


• Ref.: Oran, E. S. and J. P. Boris, "Detailed Modeling of Combustion Systems," Prog. Energy Combust. Sci., 1981

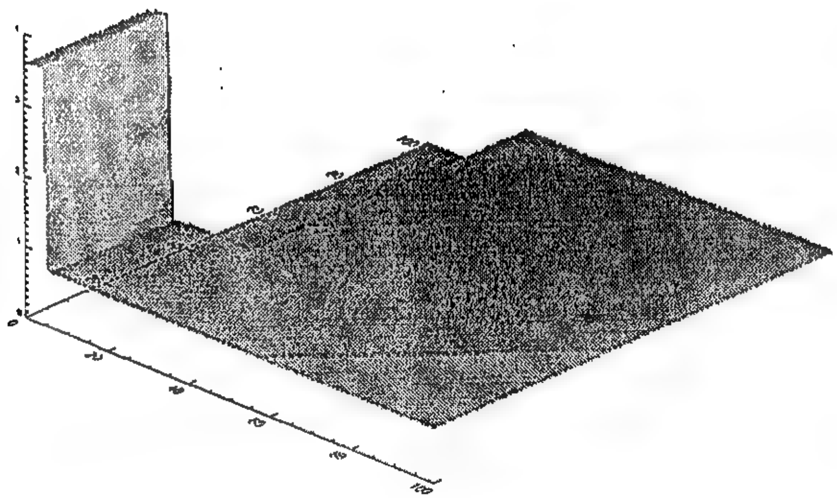
Modeling Diagram



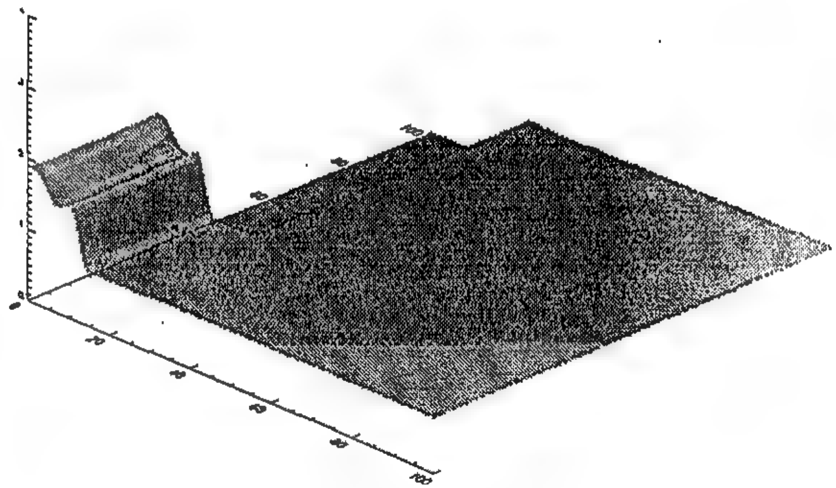




Example Results
Pressure Ratio = 5

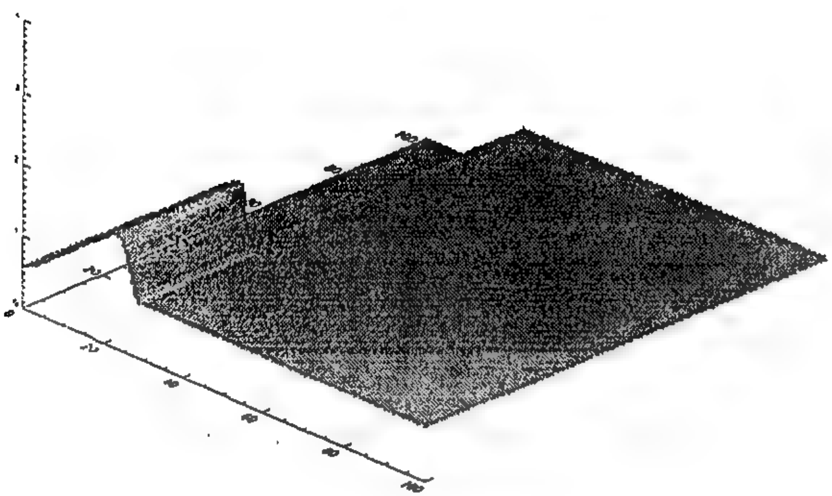


t* = 0

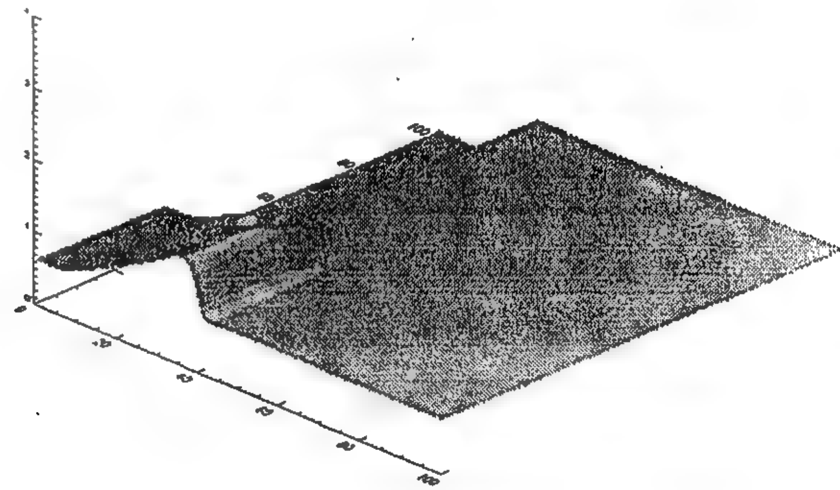


t* = 0.054

Example Results
Pressure Ratio = 5

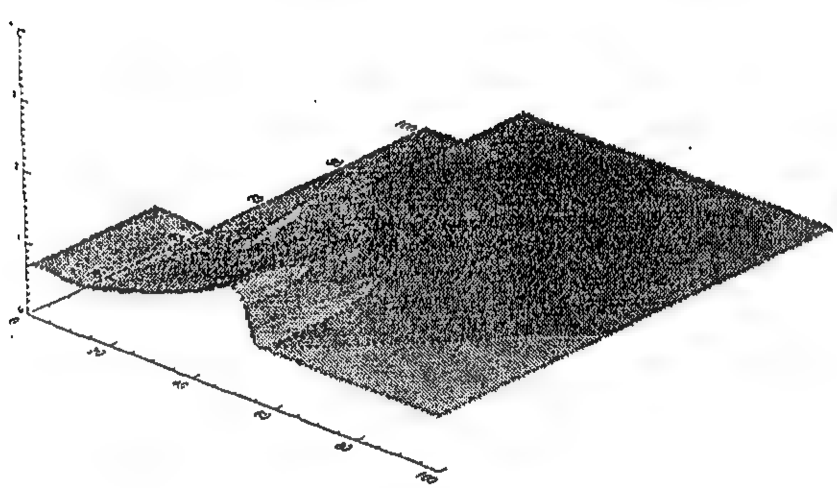


t* = 0.151

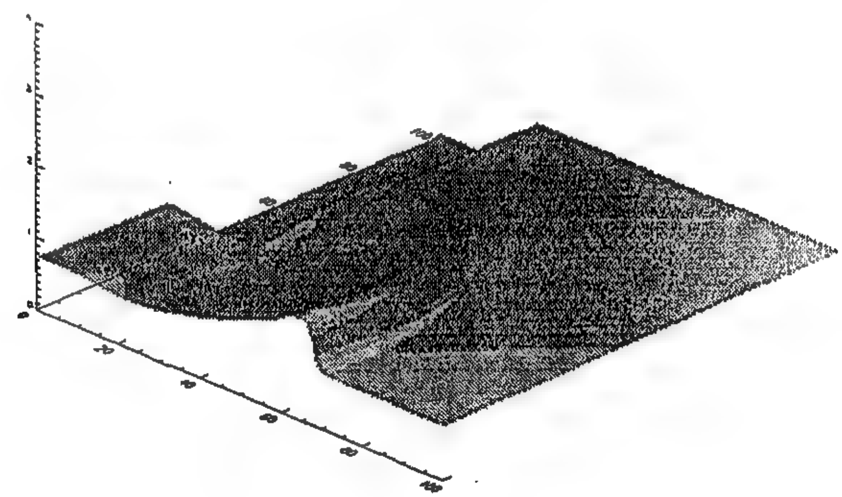


t* = 0.247

Example Results
Pressure Ratio = 5



t* = 0.349



t* = 0.451

Improvements in Plasma Density & Mixing

31

Reactive injector liners

Graded liners / current profiling

Ablation rate measurements

Modeling of ablation

Observations of density *vs* mixing

Properties of Propellant Materials

Developing copolymer reactive liners

- Nitrated ethylene / PVA copolymer
- For increasing plasma density
- For use with HAN

Ablation rate calibration

- From shock tube experiments

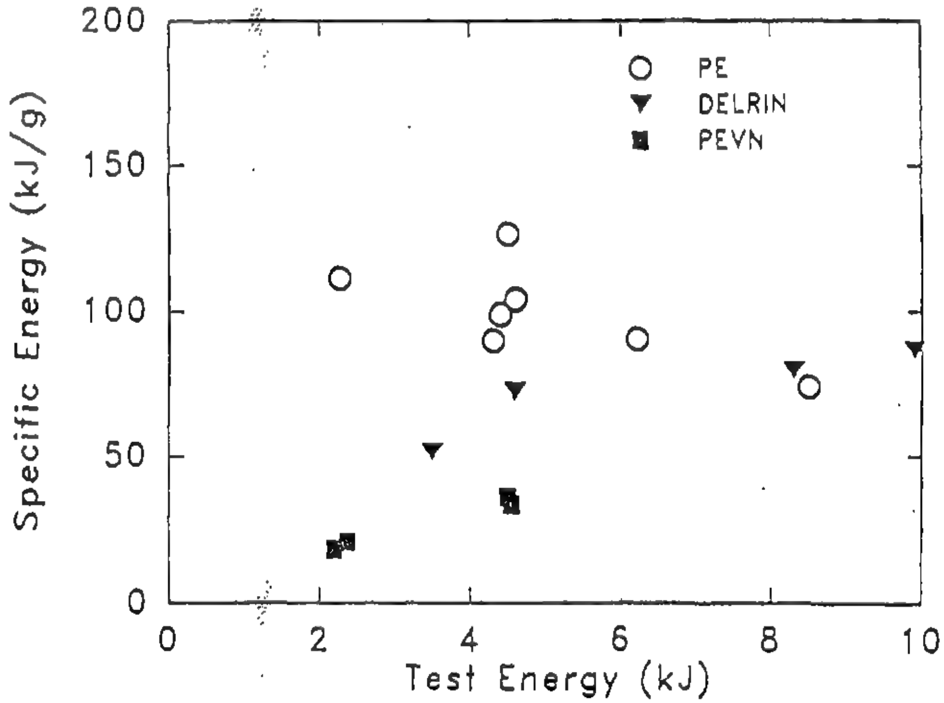
Gun simulator testing of above materials

- For plasma density effects
- For mixing improvements
- For energetics / kinetics

Ablation Data from Electrothermal Injector Tests for Three Materials

washer tests

full liner tests



- Washer tests (PEVN), preliminary safety testing
- Full liner tests, normal testing configuration
- Specific Energy --- Elec. Energy to arc / Total liner mass removed
  (Small value ---> Large mass removed)

Summary

Studying fundamental processes

Provide inputs to higher level models

Supports BRL efforts

Will answer some scaling issues

Methodical, low risk approach

DIAGNOSTICS DEVELOPMENT FOR THE ETC PROGRAM

Donald W. Sweeney, Steven Vosen, Jeffrey Gray, and Robert Armstrong
Sandia National Laboratories
Livermore, CA 94551-0969

ABSTRACT

Control of the ET process is governed by the proper coupling of plasma energy to chemical energy. Optimization requires that the mixing and combustion process be understood. The physics and chemistry of the mixing of a plasma injected into a confined liquid will be studied by combining the techniques of high-speed cinematography and emission spectroscopy. Variation of the mixing chamber geometry and of the liquid, with increasing energetic content (e.g., from water to methanol to hydroxyl ammonium nitrate), will allow the effects of chemistry on plume development and mixing to be studied.

DIAGNOSTIC DEVELOPMENT FOR THE ETC PROGRAM

JANNAF Workshop
ETC Modeling & Diagnostics

July 9-11, 1991

Donald Sweeney, Steve Vosen,
Jeff Gray and Rob Armstrong

Combustion Research Facility
Sandia National Laboratories

We Will Review Three Components of the CRF Program

1. Diagnostics of plasma generation and fluid mixing
2. Chemical and thermal ablation studies
3. Laser-induced plasmas for ETC development

Diagnostics for measuring gas generation and plasma behavior will be developed for gun conditions

Development of diagnostics for use at gun conditions is underway to quantify:

1) plasma behavior, and
2) gas generation rates.

Development will progress through three pressure regimes:

1) Low Pressure : P $<$ 1 kpsi (FY 91),
2) Medium Pressure: P = 1 - 15 kpsi (FY 92), and
3) High Pressure: P = 10 - 100 kpsi (FY 93).

At low pressures we will observe fluid mixing over a range of pressures

Pressures: 15-1000 psi

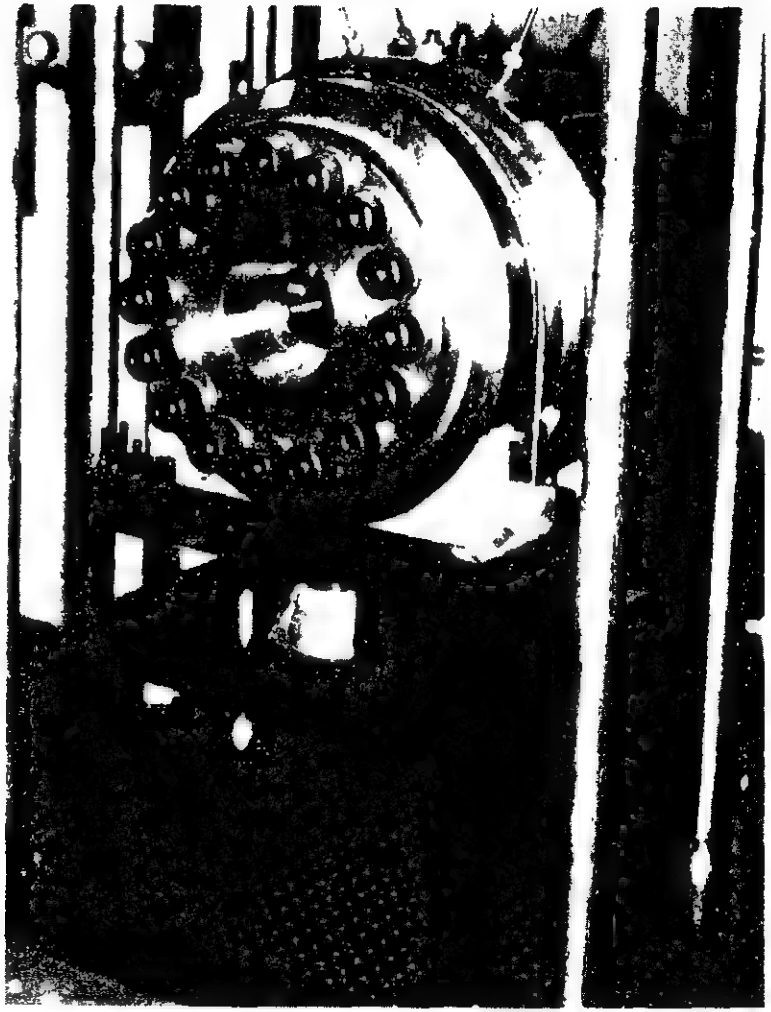
Process/Location	Diagnostic Technique • Measurement
Gas Generation/ Mixing Chamber	Photography and image processing • Develop image processing techniques, similar to those developed for liquid propellants, to quantify images of full flow-field mixing Vary energy and mixing fluid. • Determine effect of energy and fluid on evolution of mixing region.
Plasma Formation/ Plasma Cartridge	n.a. (explosive charge)

Pressure vessel

Pressure: 0 - 5000 psig

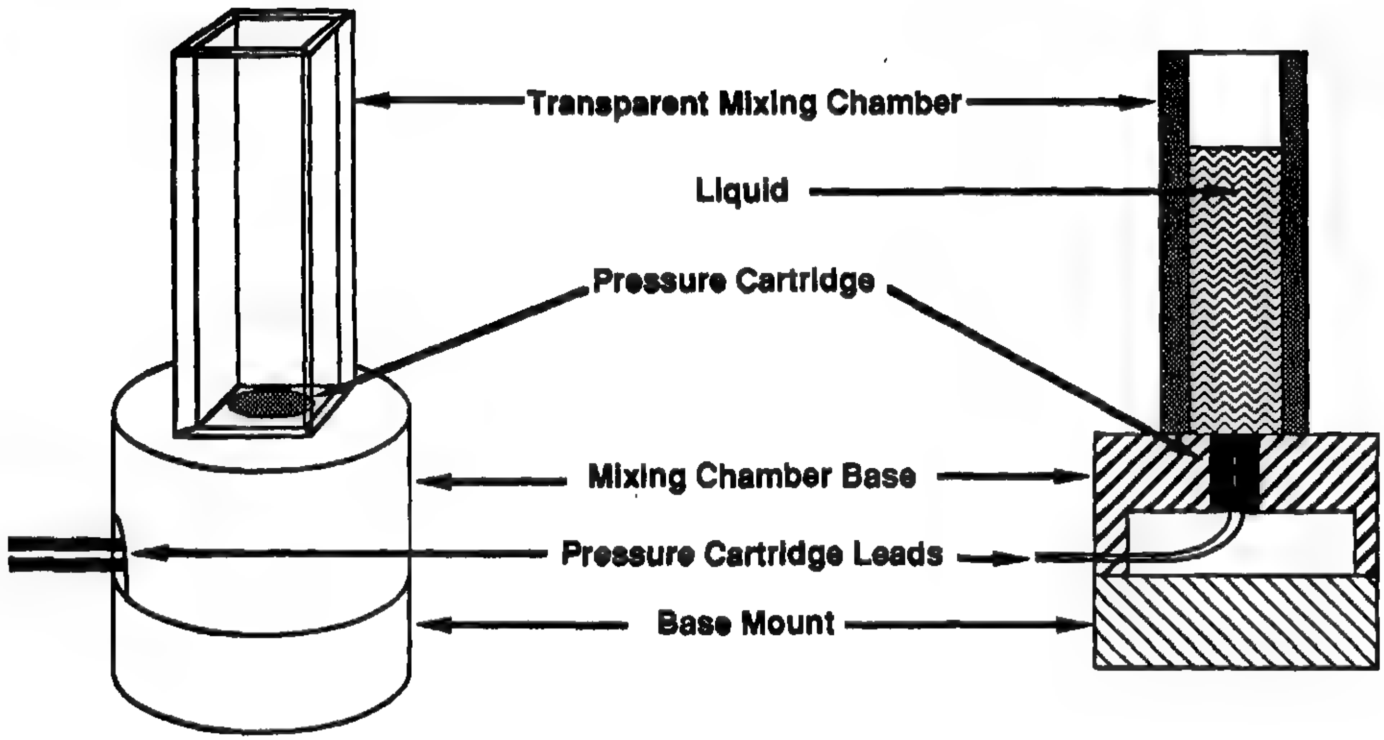
Volume: 13 liters

Windows: 4, 100 mm dia.



40

Mixing/image processing experiments will be done in a low pressure apparatus

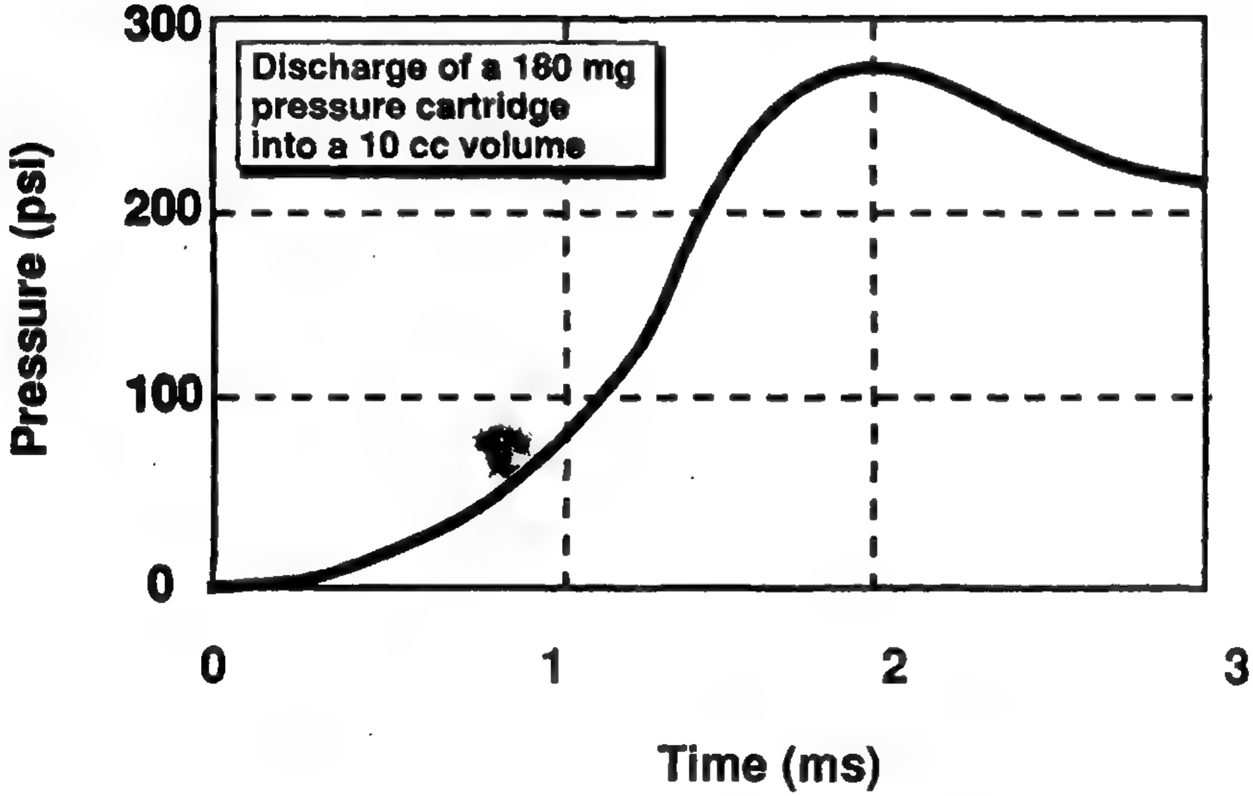


... ridge deliver energy to ... low pressure mixing chamber

... ive pressure cartridges are ... generate a hot jet of gas

Charge ... mg
... 250 J

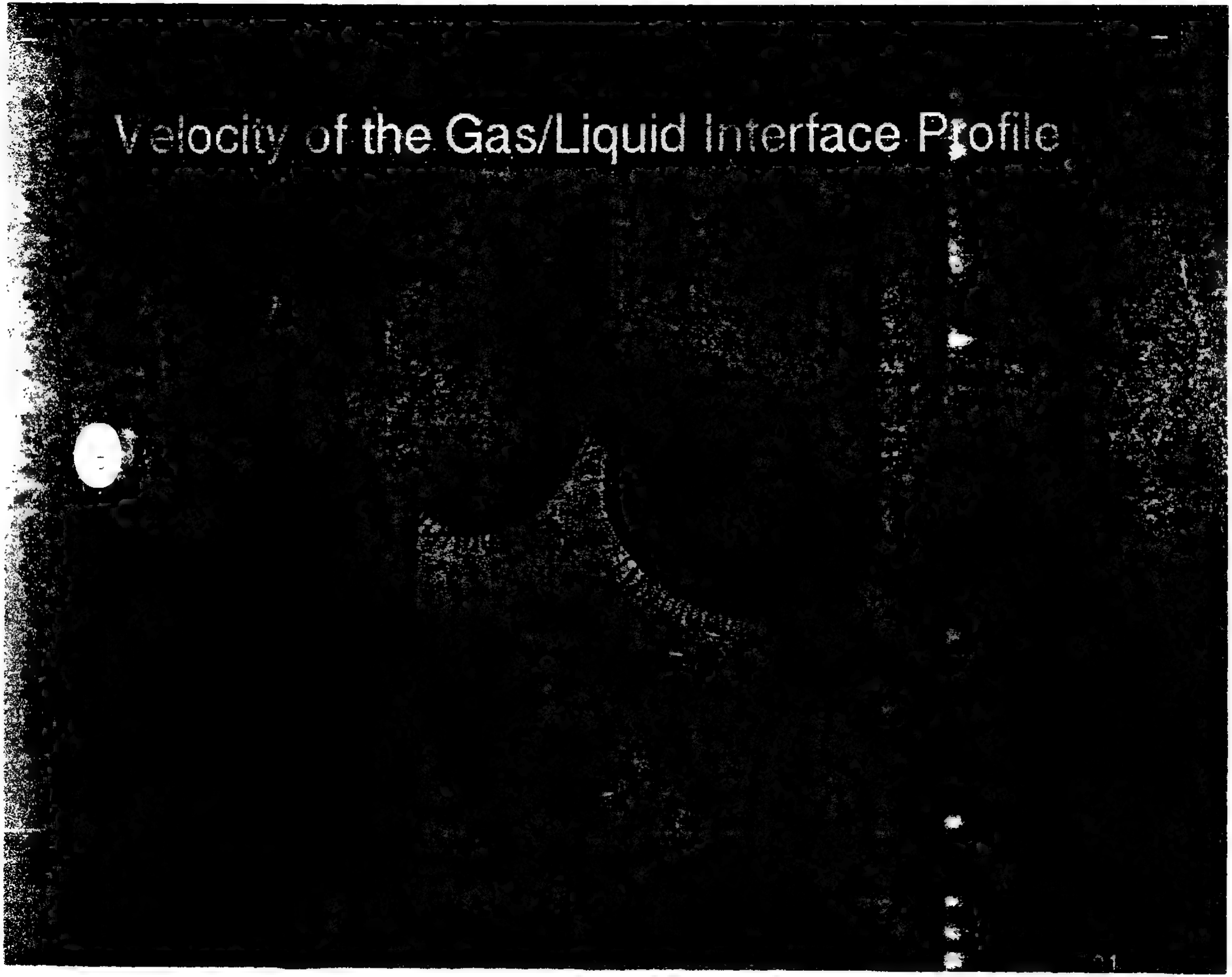
Pressure cartridges release 200 Joules in 1 - 2 milliseconds



43

0 FPS Photographs of Burning LP 1846

44


Velocity of the Gas/Liquid Interface Profile

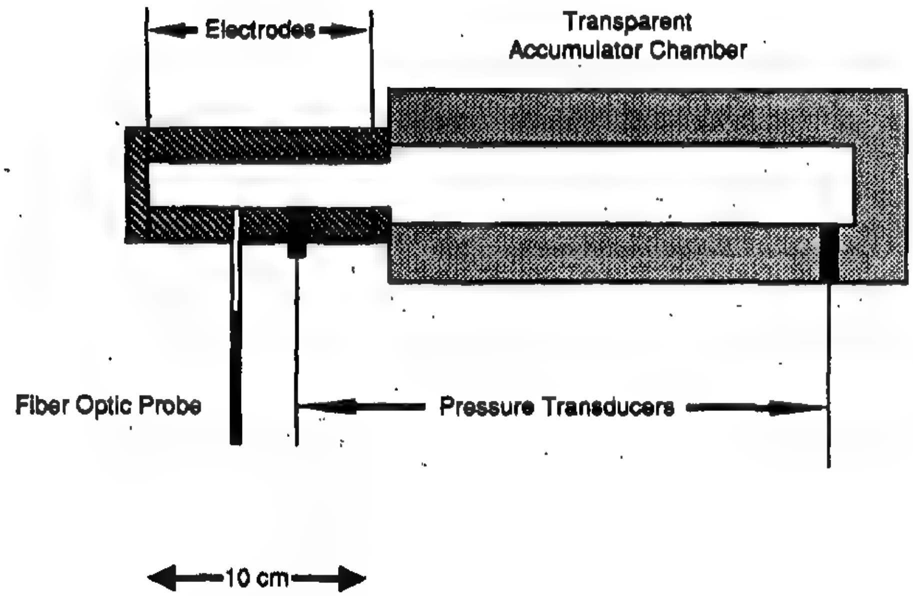
Relevant gas generation mechanisms and plasma behavior will be studied at medium pressure

Pressures: 1-15 kpsi

Process/Location	Diagnostic Technique • Measurement
Gas Generation/ Mixing Chamber	Photography/image processing • Characterize mixing over a range of conditions. (Maximum pressure overlaps with high pressure studies)
Plasma Formation/ Plasma Cartridge	Time resolved emission • Plasma stability Spectrally resolved emission • Plasma temperature • Electron density • Sheath temperature • Identify Species Heat transfer probes • Radiative heat transfer • Conductive heat transfer

A Medium Pressure Apparatus will be used to study plasma characteristics and flow-field mixing

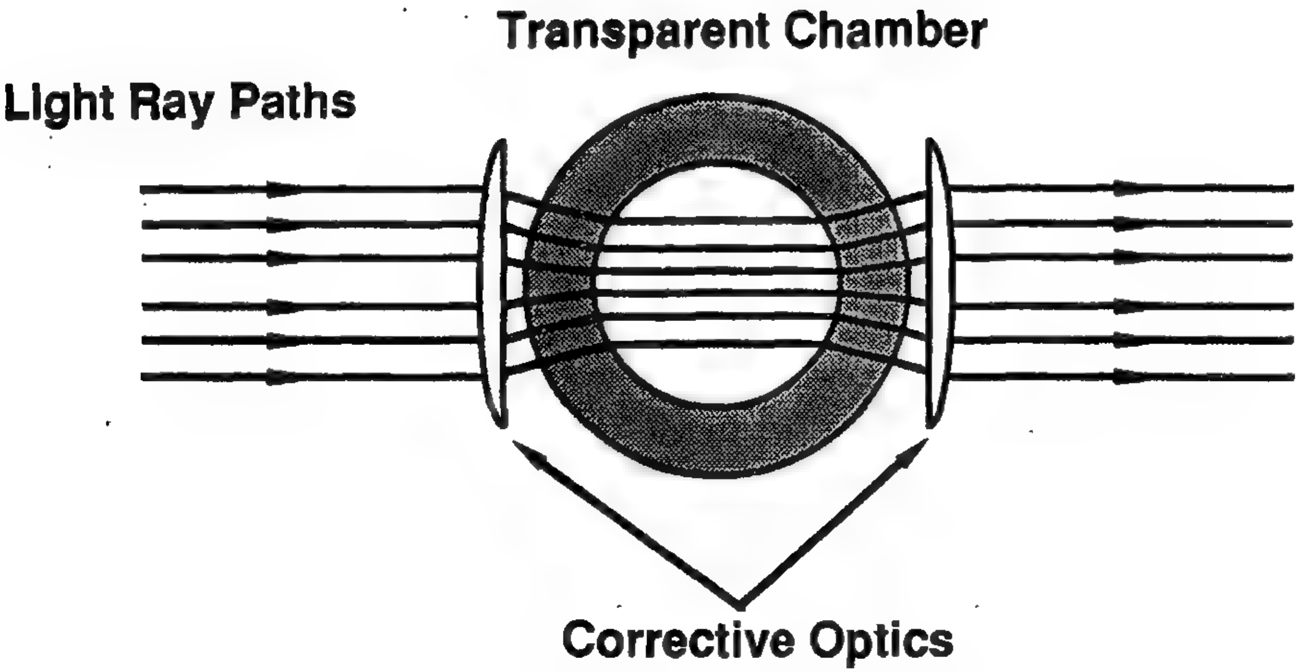
Schematic of medium pressure apparatus



The transparent chamber with corrective optics will allow for Schlieren photographic measurements

End View of Chamber:

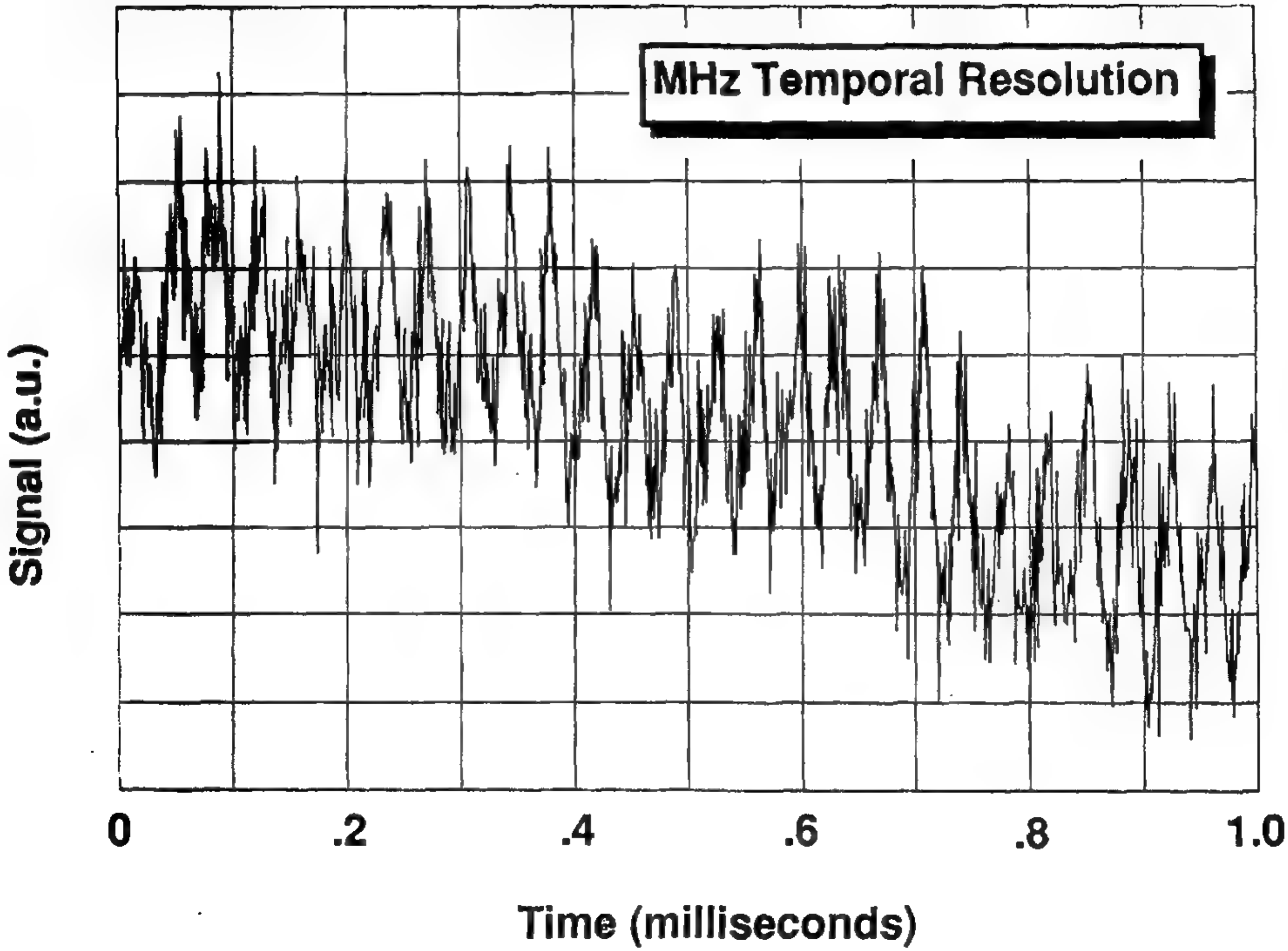
48

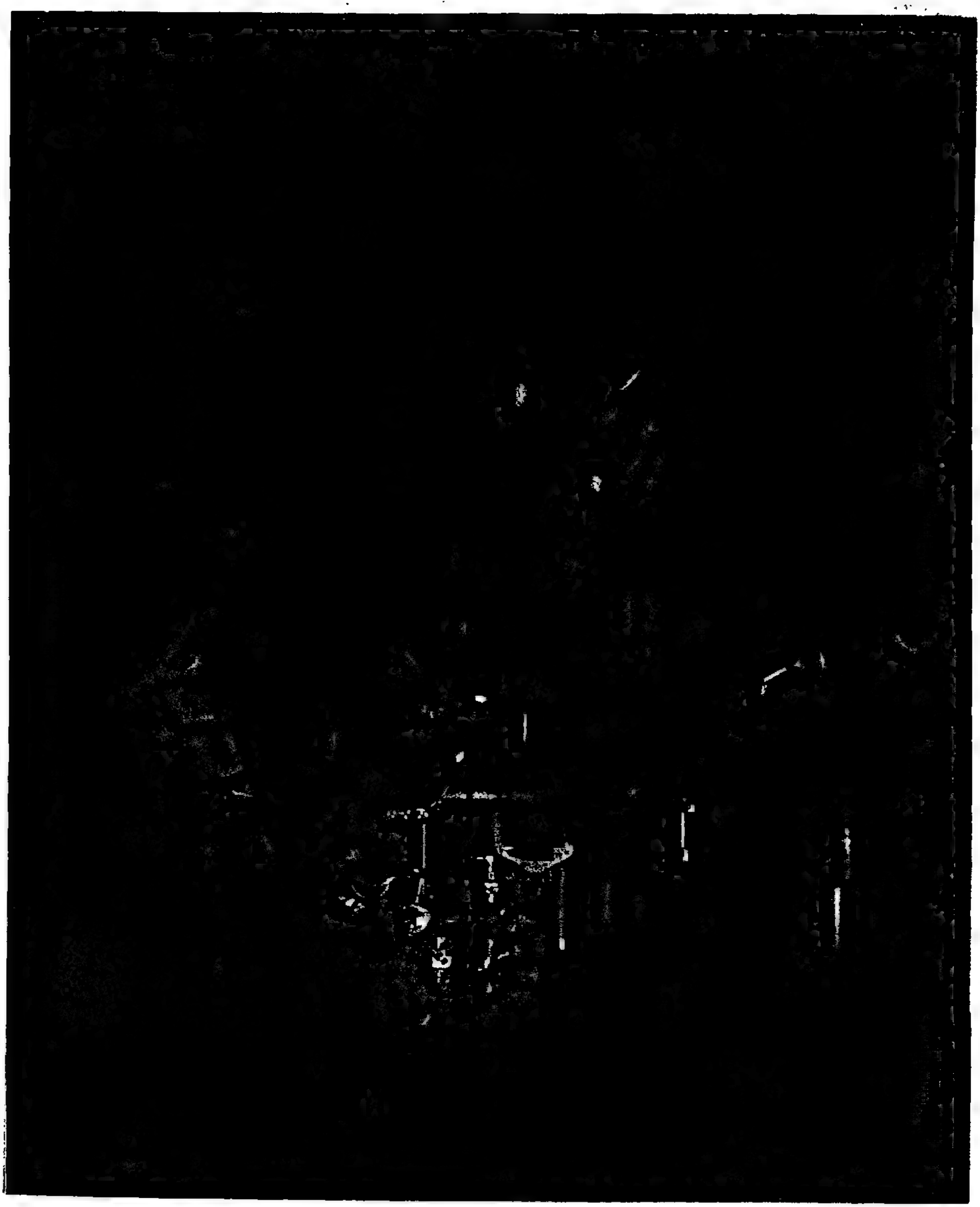


Fiber optic probes will provide spectral information from the plasma cartridge and in high pressure experiments

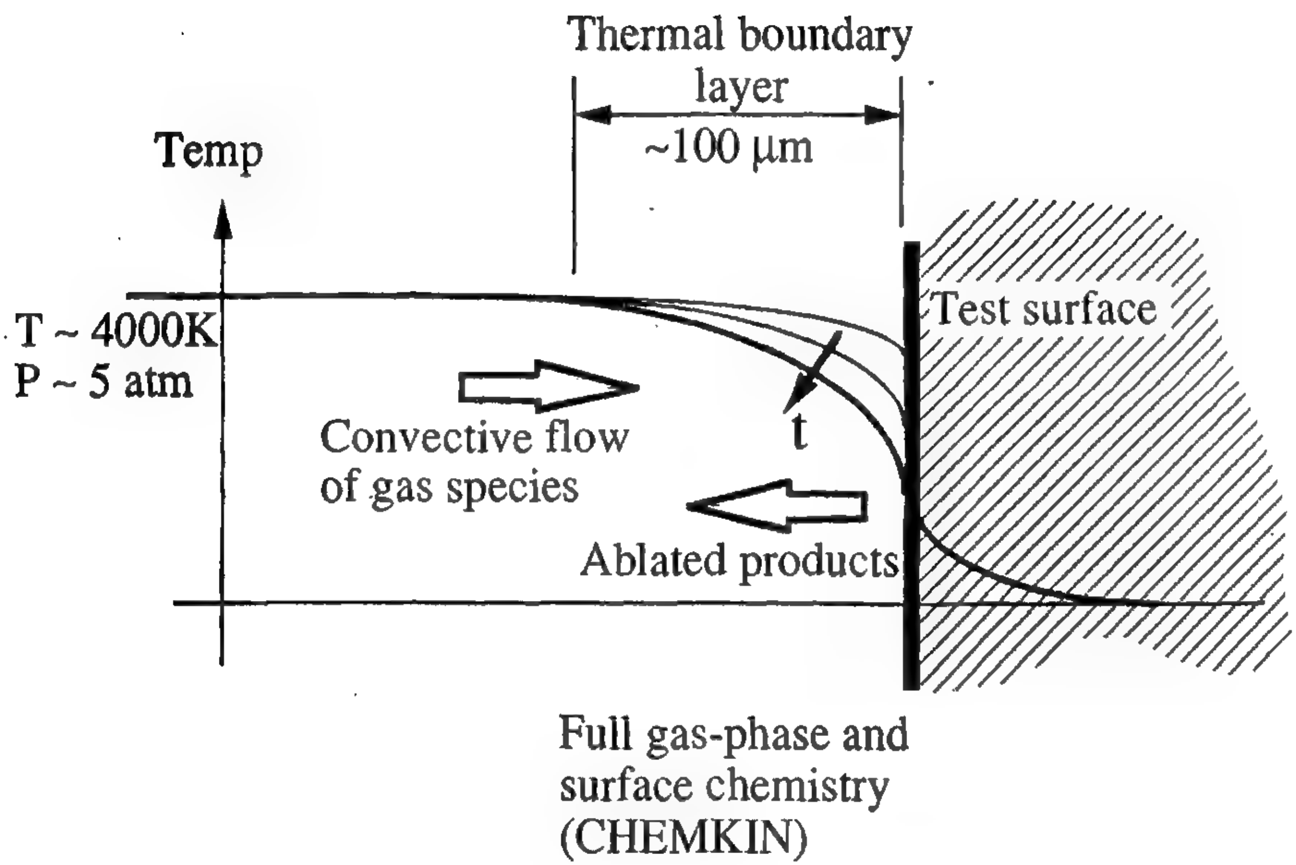
Fiber Optic Probers have been designed and used to measure light emission from the Sandia Liquid Propellant Injector/Combustor at high pressures.

Fiber optics will provide spectral and/or temporal information



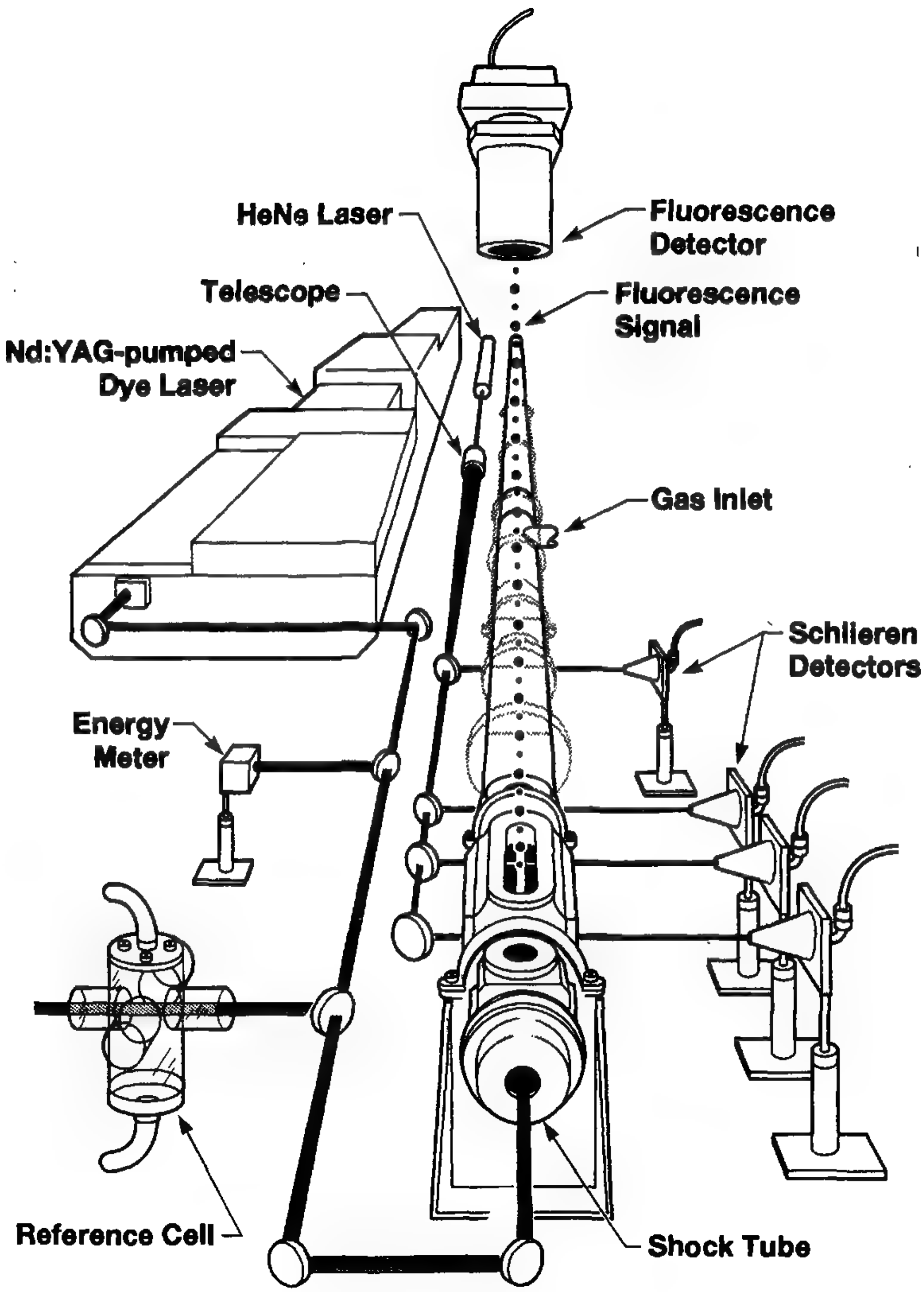


The shock tube provides a controlled environment to observe both thermal and chemical ablation processes



52

Experimental Schematic



Chemical ablation is initiated by seeding the shock tube

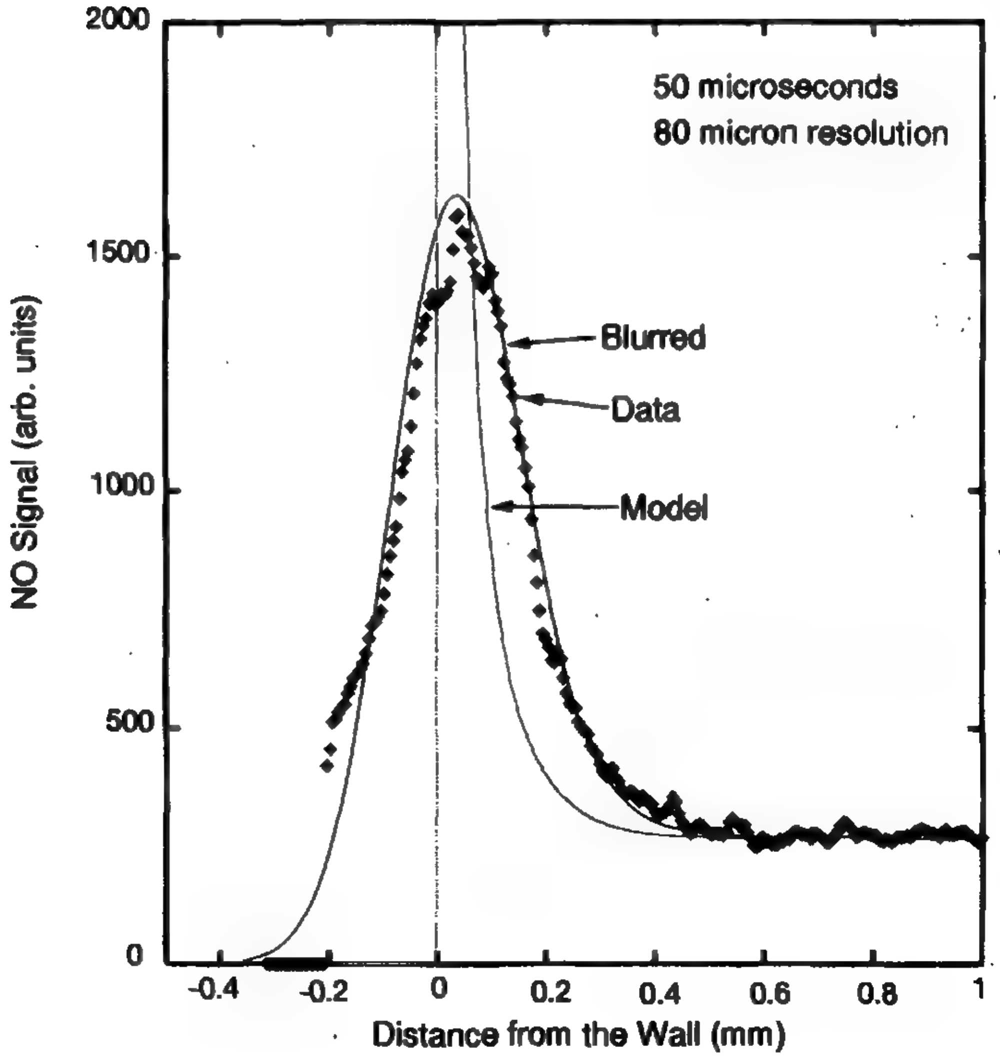
$$N_2O \rightarrow N_2 + O$$

The O-atoms attack the surface and generate OH

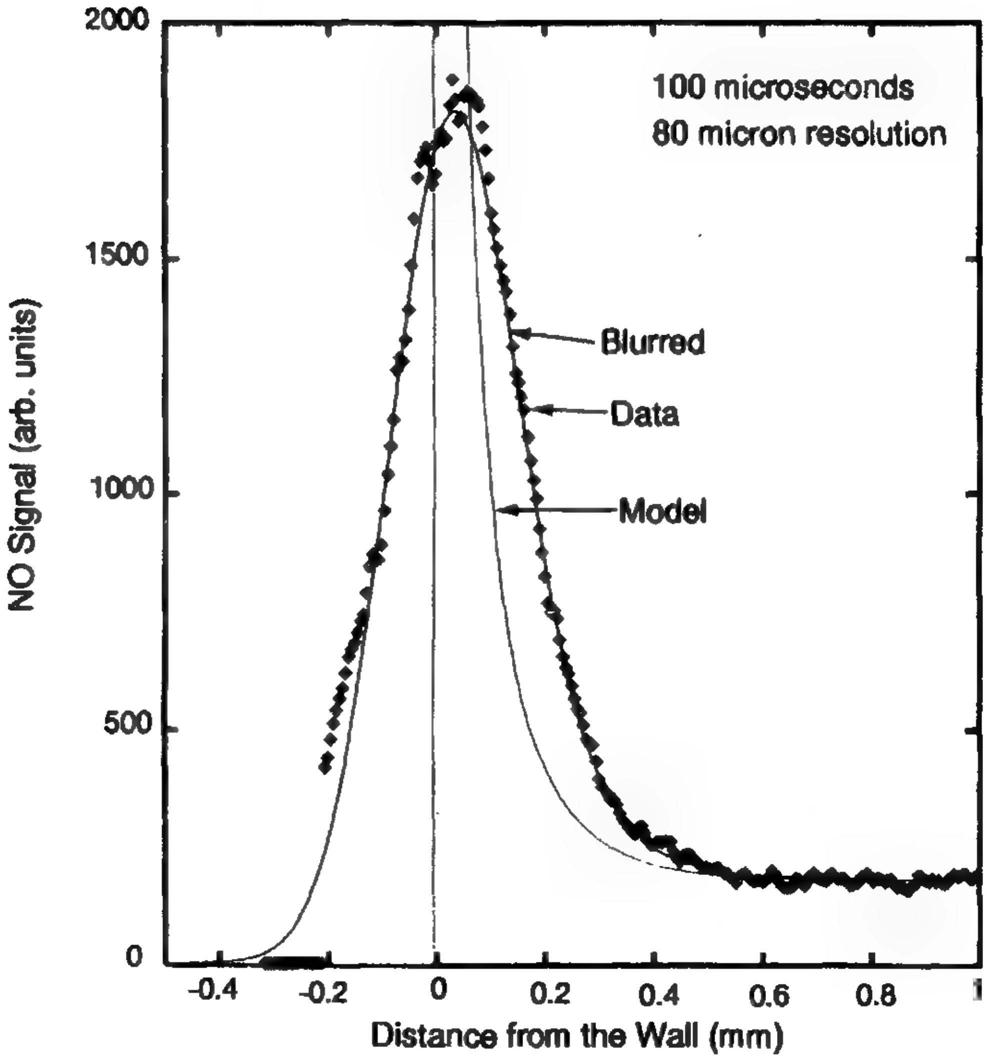
$$O + (\text{-}CH_2\text{-})_n \rightarrow OH + (\text{-}CHCH_2\text{-})_n$$

OH is observed using LIF

Data and model agree when the model is blurred to account for instrument function

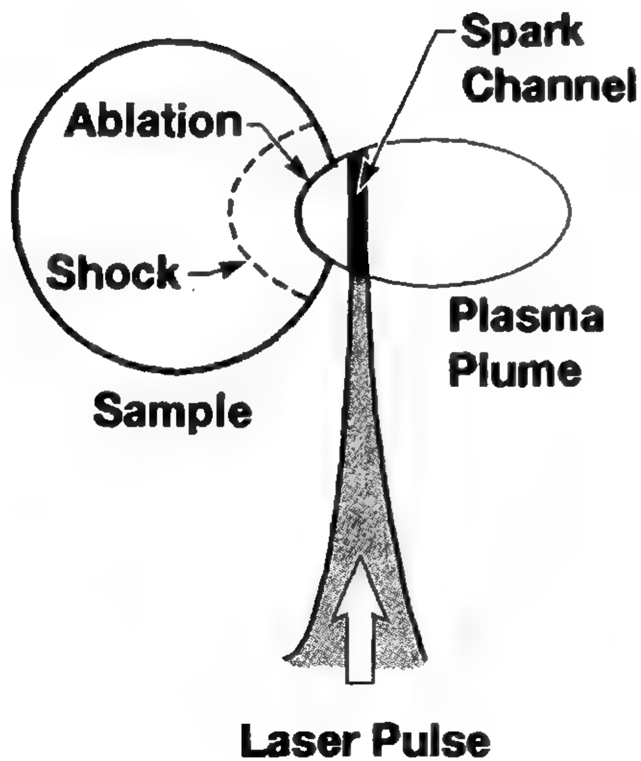


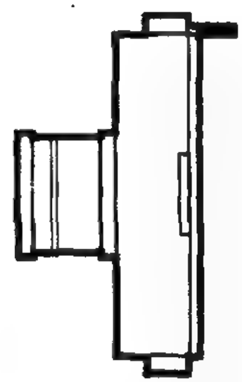
Data and model agree when the model is blurred to account for instrument function



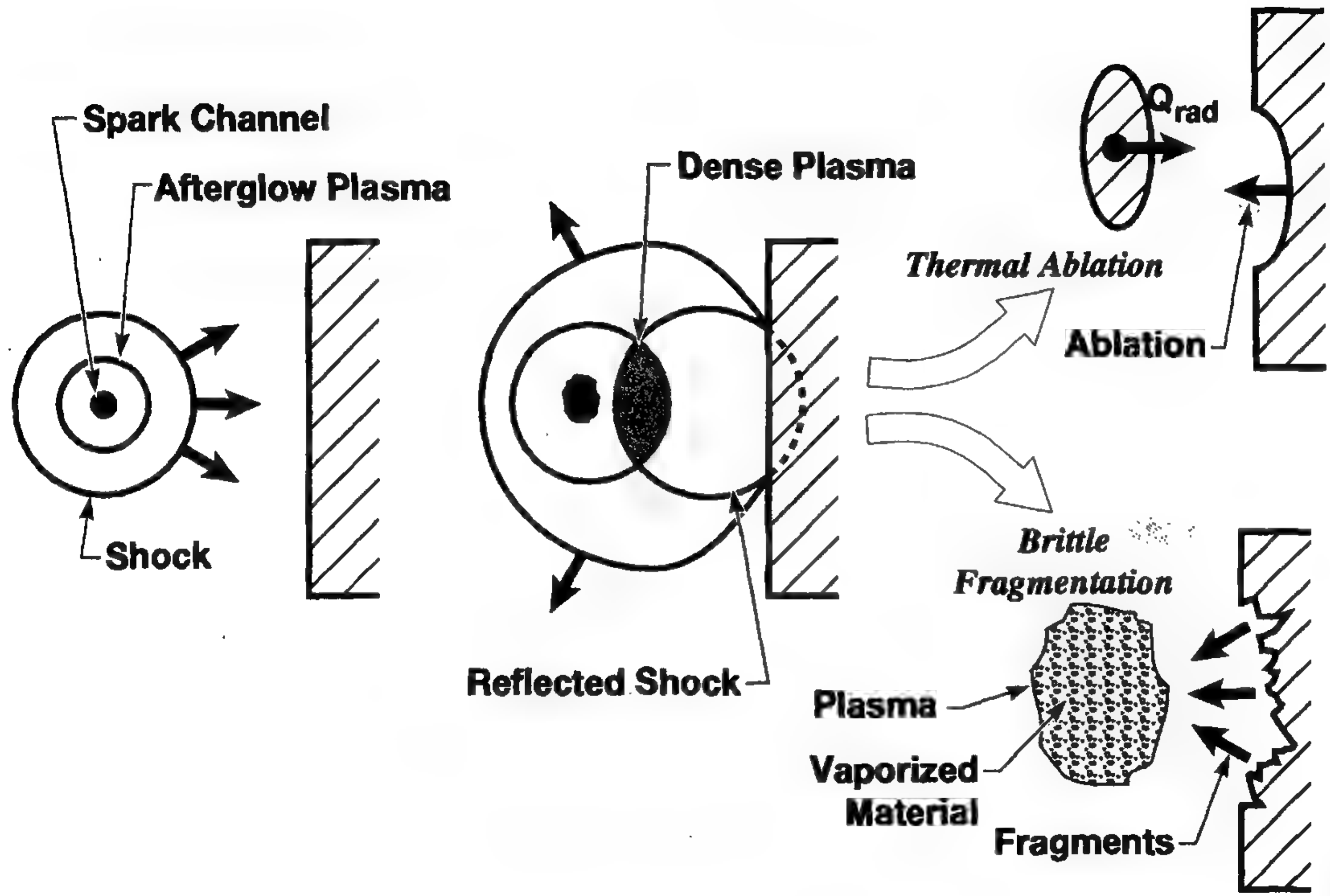
ETC Combustion is being studied using Laser - Plasma Ablation

- Spectroscopy
- Imaging





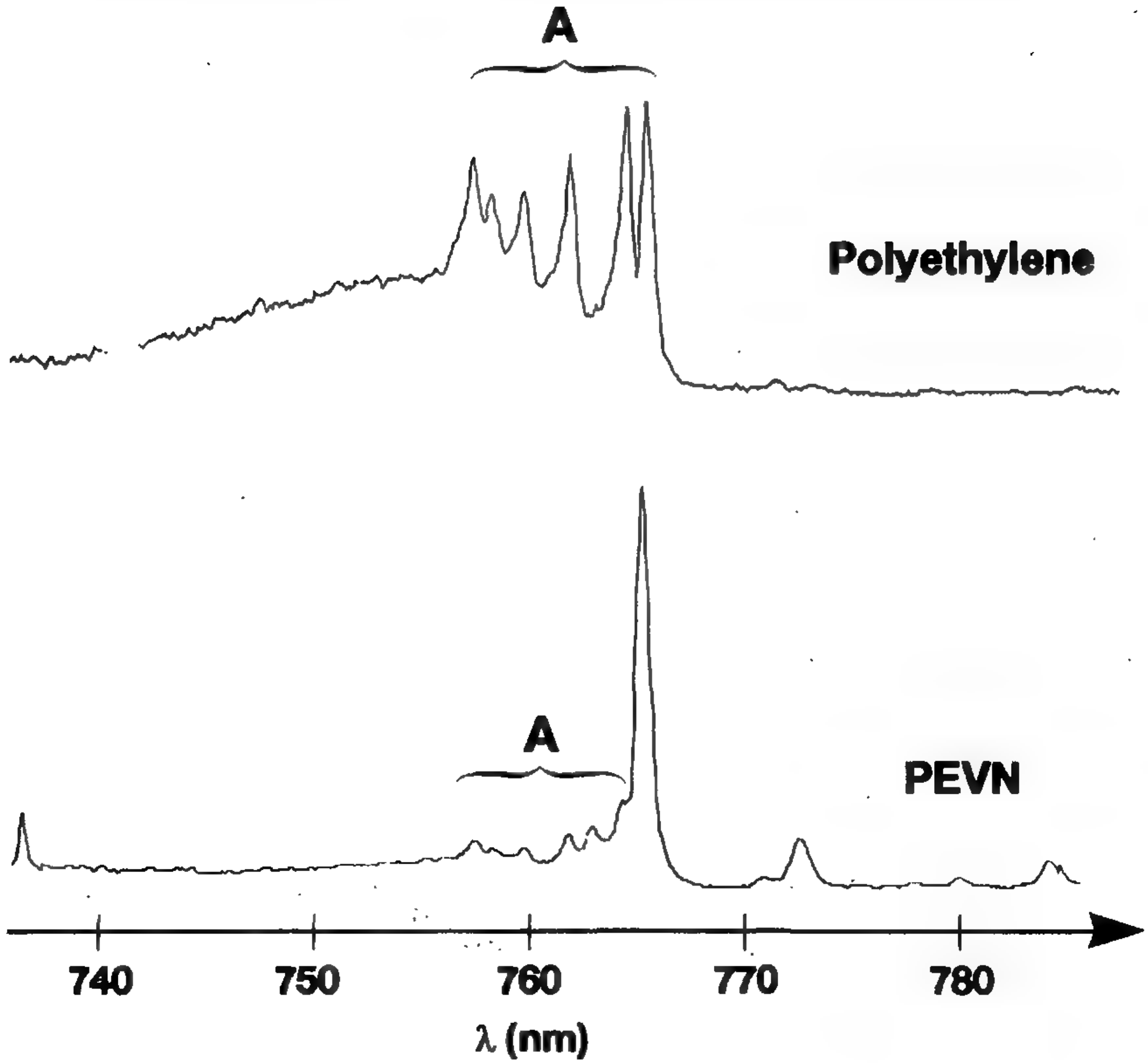
Laser - induced plasmas help discern various ETC processes



Variations in Test Conditions

- Plasma power density ranges from 10^8 to 10^{11} W/cm^3
- Samples of PE, PEVN, etc.
- Reflected shock conditions to > 6000 K, > 10^3 atm
- Plasma formation in air, He, Ar, vacuum, and water
- Temporal resolution of 20 ns, Spatial resolution of 20 μm
- Spectroscopy from 0.2 to 1.0 μm

Laser - Ablation Spectroscopy Reveals Plasma Species for Different Materials



Time - Resolved Imaging Shows Ablation Rates for Different Materials

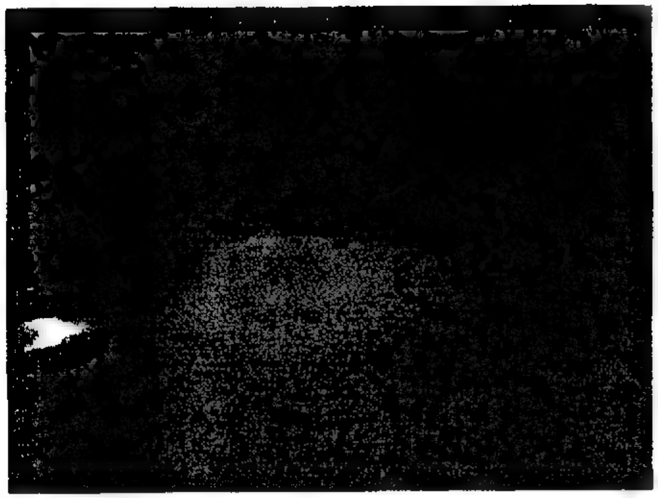
Polyethylene at low pressure

0 delay

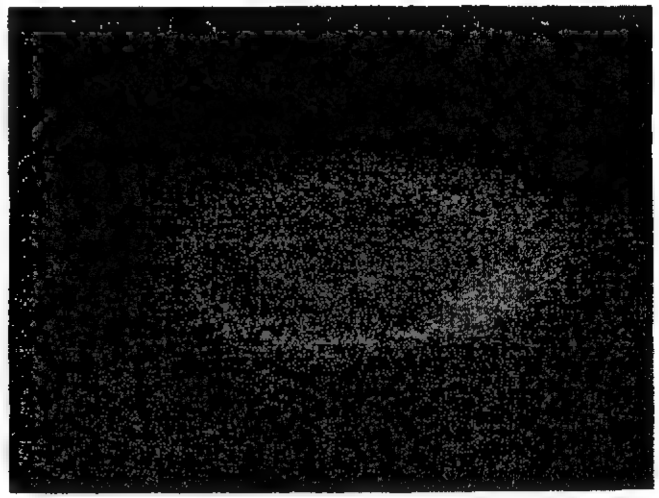
50 ns delay

Ablation Rates may be related to the Energetics of Materials

PEVN at low pressure



0 delay



50 ns delay

Laser Plasmas Simulate Conditions on an Optically Accessible Laboratory Scale

- Highest power density achieved in Sandia tests ($\geq 10^{10}$ W/cm^3)
- Pressures and temperatures in the same range as gun conditions
- High repetition rate (10 Hz) allows us to perform a large matrix of tests studying ablation, and possibly mixing
- Provides a diagnostics testbed for full scale tests

INTENTIONALLY LEFT BLANK.

DEVELOPMENT OF AN UPWIND/IMPLICIT COMPUTATIONAL MODEL FOR THE ADVANCEMENT OF ARMY ETC GUNS

N. Sinha, A. Hosangadi, and S. M. Dash
Science Applications International Corporation
Fort Washington, PA

ABSTRACT

A first-principles, state-of-the-art computational model based on the CRAFT Navier-Stokes solver is under development for the U.S. Army to simulate fluid dynamic and electro-thermo-chemical processes in ETC guns. The model will incorporate physics submodules developed from diagnostics by the team of SAIC, BRL and SNL scientists as well as national and international efforts coordinated with the Army.

This presentation will provide an overview of the 1D/2D/3D finite-volume upwind (Roe/TVD)/implicit numerics in CRAFT and its strongly-coupled treatment of combustion chemistry and multi-phase non-equilibrium processes (presently limited to dilute particulates). Current work focussed on the ETC gun problem includes dynamic grid capabilities with solution adaptive features, and research towards incorporating complex equations of state into higher-order Riemann based solvers such as the Roe/TVD scheme implemented. A building-block approach upgrade of CRAFT to simulate ETC processes will be described along with representative calculations which exhibit present capabilities.

DEVELOPMENT OF AN UPWIND/IMPLICIT COMPUTATIONAL MODEL FOR THE ADVANCEMENT OF ARMY ETC GUNS

N. Sinha, A. Hosangadi, and S. M. Dash
Science Applications International Corporation
Fluid and Propulsion Sciences Operation
501 Office Center Drive, Suite 420
Fort Washington, PA 19034-3211
Phone: 215/542-1200 FAX: 215/542-8076

JULY 9-11, 1991

Presented at:

JANNAF WORKSHOP ON ETC MODELING AND DIAGNOSTICS

U.S. ARMY BALLISTICS RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

SAIC® An Employee-Owned Company
Science Applications International Corporation

TOPICS

- APPROACH TO BE TAKEN
- CRAFT 1D/2D/3D UPWIND/IMPLICIT FINITE-VOLUME CODE
  - HISTORY
  - EQUATIONS/NUMERICS
  - STRONGLY-COUPLED CHEMISTRY
  - COUPLED ANALYSIS OF DILUTE PARTICULATES
  - DYNAMIC GRID
- RELATED APPLICATIONS
- CRAFT/ETC DEVELOPMENT
  - ADAPTION TO ETC ENVIRONMENT
  - COMPLEX EQUATIONS OF STATE/RIEMANN PROBLEM
  - GAS/LIQUID PROBLEMS

⋮

- PRELIMINARY APPLICATIONS (BRL PROGRAM INITIATED 6/1/91)

BRL APPROACH FOR ETC GUN SIMULATION

- EMPHASIS ON UNDERSTANDING "PHENOMENOLOGY" AND INFLUENCE OF THERMOCHEMISTRY AND PHYSICS ON GUN PERFORMANCE

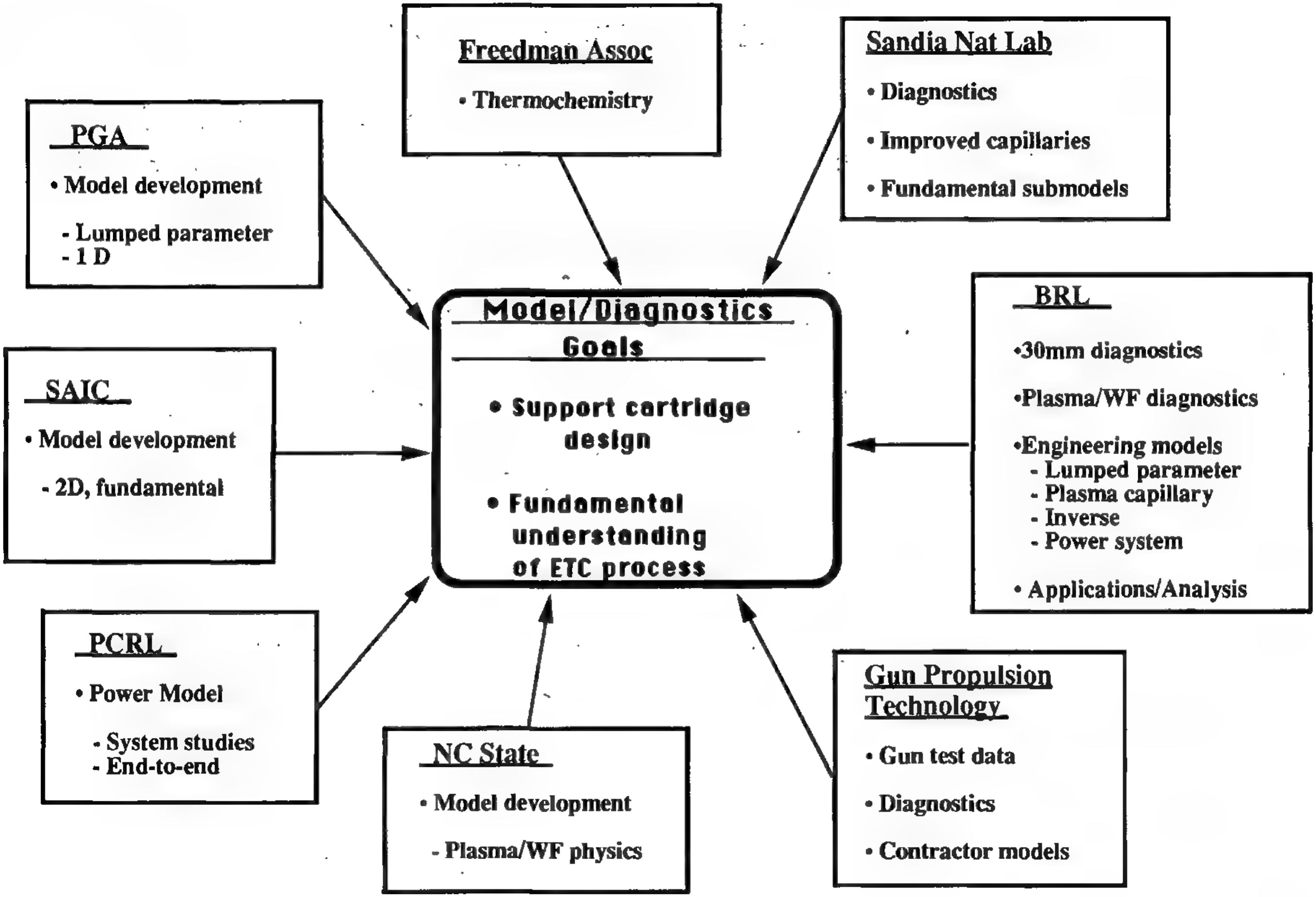
- EXPERIMENTAL DATA USED TO SUPPORT DEVELOPMENT OF "FIRST-PRINCIPLES" CFD SIMULATION CODE AND TO ENHANCE UNDERSTANDING OF PHENOMENOLOGY

  - NO ATTEMPTS TO "TUNE" THERMOCHEMICAL/ PHYSICAL PARAMETERS TO MATCH DATA

- BUILDING BLOCK APPROACH FOR UNDERSTANDING PHENOMENOLOGY

  - EXPLORE INDIVIDUAL EFFECTS

Army ETC Modeling & Diagnostics



mod/diag.may91

FEATURES OF CRAFT FOR ETC GUN SIMULATION

FEATURE	ADVANTAGE
1D/2D/AXI/3D RUN OPTIONS	CAN DO FAST PRELIMINARY DESIGN STUDIES (1D) AND DETAILED SIMULATION (2D/AXI/3D) IN SINGLE CODE
FINITE-VOLUME IMPLICIT CONSERVATIVE FORMULATION	CONSERVATIVE/FINITE-VOLUME NUMERICS YIELDS ACCURATE FLUX BALANCES – EQUATIONS STRONGLY COUPLED; IMPLICIT NUMERICS ELIMINATES STABILITY/ STEP-SIZE PROBLEMS AND PERMITS RESOLVING NEAR-WALL BOUNDARY LAYERS
ROE/TVD UPWIND NUMERICS	ROE IS REIMANN BASED DIFFERENCING FOR ACCURATE CONVECTIVE/WAVE TRACKING; TVD IS HIGHER-ORDER EXTENSION; NO ARTIFICIAL DISSIPATION REQUIRED FOR STABILITY
BLOCK MATRIX INVERSION WITH INNER NEWTON ITERATION	ROBUST INVERSION PROCEDURE PERMITS TAKING LARGE TIME-STEPS; INNER ITERATIONS PERMITS ELIMINATING ALL FACTORIZATION/LINEARIZATION ERRORS WITHIN STEP
STRONGLY-COUPLED, FULLY-IMPLICIT CHEMISTRY	CHEMICAL SPECIES ARE PART OF COUPLED EQUATION SET FOR ACCURACY/ROBUSTNESS; CHEMICAL SOURCE TERMS TREATED FULLY-IMPLICITLY TO ELIMINATE STIFFNESS
STRONGLY-COUPLED, FULLY-IMPLICIT TURBULENCE MODELS	TURBULENCE MODEL EQUATIONS ARE PART OF COUPLED EQUATION SET FOR ACCURACY/ROBUSTNESS; TURBULENCE SOURCE TERMS TREATED FULLY-IMPLICITLY TO ELIMINATE STIFFNESS
IMPLICIT/UPWIND DISPERSED PHASE SOLVER	PARTICULATE EQUATIONS SOLVER ON SAME GRID AS FLUID PHASE USING SAME IMPLICIT/UPWIND NUMERICS; STRONG FLUID/PARTICLE COUPLING AND IMPLICIT SOURCE TERM TREATMENT
DYNAMIC GRID, SOLUTION ADAPTIVE MODULE	GRID MOVES/DEFORMS IN ACCORDANCE WITH BOUNDARY MOTION (PROJECTILE) AND REDISTRIBUTES USING NASA/AMES SAGE MODULE

EVOLUTION OF METHODOLOGY IN CRAFT CODE

- UPWIND/IMPLICIT FINITE-VOLUME METHODOLOGY (ROE/TVD) APPLIED TO EXTERNAL AERODYNAMIC FLOWFIELDS ~ 1986-1988. Reference: Walters and Thomas, "Advances in Upwind Relaxation Methods," State of the Art Surveys on Computational Fluid Mechanics, ASME Pub., 1988.

- EXTENSIONS OF ROE/TVD METHODOLOGY TO MULTI-COMPONENT/REAL GAS FLOWS WITH CHEMICAL/THERMAL NONEQUILIBRIUM ~ 1988-1989. Reference: Liu and Vinokur, "Upwind Algorithms for General Thermo-Chemical Nonequilibrium Flows," AIAA Paper 89-0201, Jan. 1989.

- EXPLORATORY STUDIES OF ROE/TVD NUMERICS FOR UNSTEADY FLOWS, ACCURATE WAVE PROPAGATION IN DUCT (RESONANCE TUBE) ~ 1989. Reference: Ridder and Beddini, "Time-Accurate Finite-Volume Method for Propulsion Chamber Flows," AIAA Paper 89-2554, July 1989.

- EXTENSIONS OF ROE/TVD METHODOLOGY FOR PROPULSIVE FLOWS WITH COMBUSTION CHEMISTRY, ADVANCED TURBULENCE MODELS ~ 1989-1991. Reference: Dash, "Advanced Computational Models for Analyzing High-Speed Propulsive Flowfields," 1990 JANNAF Propulsion Meeting, Oct. 1990.

- EXTENSIONS OF ROE/TVD METHODOLOGY FOR UNSTEADY ROCKET PLUME PROBLEMS WITH MULTI-PHASE NONEQUILIBRIUM ~ 1989-1991. Reference: Sinha, Hosangadi and Dash, "The CRAFT NS Code and Preliminary Applications to Unsteady, Reacting, Multi-Phase Plume Flowfield Problems," 1991 JANNAF Plume Meeting, May 1991.

- EXPLORATORY STUDIES OF ROE/TVD METHODOLOGY FOR GUN FLOWFIELDS WITH DYNAMIC GRID EXTENSIONS ~ 1990-1991. Reference: Hosangadi and Sinha, "Development of a Dynamic Grid Navier-Stokes Solver for Computing Electro-Thermo-Chemical Gun Configurations," SAIC/TR-88, Dec. 1990.

SYNERGISM OF CRAFT WITH OTHER DoD & NASA EFFORTS

- NUMERICS IN CRAFT REPRESENTS CURRENT STATE-OF-THE-ART FOR VISCOUS, CHEMICALLY-REACTING FLOWS

- ALL CURRENT NATIONAL PROGRAMS ARE IMPLEMENTING SUCH NUMERICS FOR REAL PROBLEMS

  - NATIONAL AEROSPACE PLANE (NASP) PROGRAM (GASP CODE, USA CODE, SCHAFT/CRAFT CODES, ...)
    → SCRAMJET PROPULSION

  - SDIO PROGRAM (GASP CODE, SCHAFT/CRAFT CODES)
    → MISSILE JETS/PLUMES

  - HIGH-SPEED RESEARCH PROGRAM (HSRP)
    → AIRCRAFT JETS/PLUMES

- 6.1 RESEARCH PROGRAMS USING THIS CLASS OF NUMERICS AS TOOL TO EXPLORE PHYSICS

  - COMBUSTION INSTABILITY IN ROCKETS/RAMJETS

  - DIRECT OR LARGE EDDY TURBULENCE SIMULATION

- SAIC IS IMPLEMENTING VERSIONS OF CRAFT TO SUPPORT SUCH PROGRAMS

RESEARCH VERSIONS OF CRAFT NS CODE

CODE NAME	CRAFT/JR	CRAFT/GF	CRAFT/RNP	CRAFT/LU
APPLICATION	HIGH-SPEED JET RESEARCH	ETC GUN FLOWFIELDS	ROCKET NOZZLES/ PLUMES	NUMERICAL RESEARCH
SPONSOR	NASA/LaRC, HSRP	BRL	MICOM	INTERNAL RESEARCH
EQUATIONS	1D/2D/AXI/3D	1D/2D/AXI/3D	1D/2D/AXI/3D	1D/2D/AXI/3D
CHEMISTRY	PERFECT GAS, TWO-STREAM	IMPERFECT GAS, COMBUSTION CHEMISTRY, MULTI-PHASE CHEMISTRY	SPF FINITE-RATE CHEMISTRY, TWO-STREAM, PERFECT GAS	PERFECT GAS
TURBULENCE	$k\varepsilon$, COMPRESSI-BILITY EXTENSIONS, ARS EXTENSIONS	$k\varepsilon$	$k\varepsilon$/Chien, COMPRESSIBILITY EXTENSIONS	$k\varepsilon$
PARTICULATES	NONE	EQUILIBRATED MIXTURE, NONEQ. LIQUID PROPELLANTS	NONEQUILIBRIUM	NONE
SOLUTION	IMPLICIT/UPWIND (Roe/TVD) STRONGLY-COUPLED FLUID/ SPECIES/ TURBULENCE (8 x 8 BLOCK INVERSION), TIME-ACCURATE OR TIME-ASYMPTOTIC	IMPLICIT/UPWIND (Roe/TVD) ON DYNAMIC GRID, TIME-ACCURATE SOLUTION, STRONGLY-COUPLED EQUATIONS, VARIABLE MATRIX SIZE	IMPLICIT/UPWIND (Roe/TVD) ON FIXED GRID, TIME-ACCURATE OR TIME-ASYMPTOTIC, STRONGLY-COUPLED EQUATIONS, VARIABLE MATRIX SIZE	LU UPGRADE FOR ROBUSTNESS, FASTER CONVERGENCE (CFL ~ 25-50)
NEW WORK	EXPLORING NEW TURBULENCE MODELS, NEW NONREFLECTIVE BC	INCLUSION OF LIQUID PHASE, GAS/ LIQUID INTERFACE, DROPLET FORMATION MODEL	ADAPTIVE GRIDDING FOR UNSTEADY MULTI- PHASE FLOWS	REWRITE OF CODE STRUCTURE TO OPTIMIZE LU STORAGE FOR 3D

CRAFT NS EQUATIONS

$$
\frac{\partial}{\partial t}\iiint Q\,dV + \iint \left(E_{i+1/2} - E_{i-1/2}\right) d\eta\, d\zeta
$$

$$
+ \iint \left(F_{j+1/2} - F_{j-1/2}\right) d\xi\, d\zeta + \iint \left(G_{k+1/2} - G_{k-1/2}\right) d\xi\, d\eta
$$

$$
= \frac{1}{Re} \iint \left(R_{i+1/2} - R_{i-1/2}\right) d\eta\, d\zeta + \iint \left(S_{j+1/2} - S_{j-1/2}\right) d\xi\, d\zeta
$$

$$
+ \frac{1}{Re} \iint \left(T_{k+1/2} - T_{k-1/2}\right) d\xi\, d\eta + \iiint D\,dV
$$

$$
Q = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ e \\ \rho_1 \\ \rho_2 \\ \rho_{n-1} \\ \rho k \\ \rho \epsilon \end{pmatrix} ; \quad
E = \begin{pmatrix} \rho \hat{U} \\ \rho \hat{U} u + \xi_x P \\ \rho \hat{U} v + \xi_y P \\ \rho \hat{U} w + \xi_z P \\ (e+P)\hat{U} \\ \rho_1 \hat{U} \\ \rho_2 \hat{U} \\ \rho_{n-1} \hat{U} \\ \rho \hat{U} k \\ \rho \hat{U} \epsilon \end{pmatrix} ; \quad
D = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \dot{\omega}_1 \\ \dot{\omega}_2 \\ \vdots \\ \dot{\omega}_{n-1} \\ P - \rho \epsilon \\ \frac{\epsilon}{k}\left(C_1 P - C_2 \rho \epsilon\right) \end{pmatrix} ; \quad
R = \begin{pmatrix} 0 \\ \ell_x \tau_{xx} + m_y \tau_{xy} + n_z \tau_{xz} \\ \ell_x \tau_{yx} + m_y \tau_{yy} + n_z \tau_{yz} \\ \ell_x \tau_{yz} + m_y \tau_{zy} + n_z \tau_{zz} \\ \ell_x \beta_x + m_y \beta_y + n_z \beta_z \\ \mu\left(\ell_x \rho_{1x} + m_y \rho_{1y} + n_z \rho_{1z}\right) \\ \vdots \\ \mu\left(\ell_x \rho_{nx} + m_y \rho_{ny} + n_z \rho_{nz}\right) \\ \mu\left(\ell_x k_x + m_y k_y + n_z k_z\right) \\ \mu\left(\ell_x \epsilon_x + m_y \epsilon_y + n_z k_z\right) \end{pmatrix}
$$

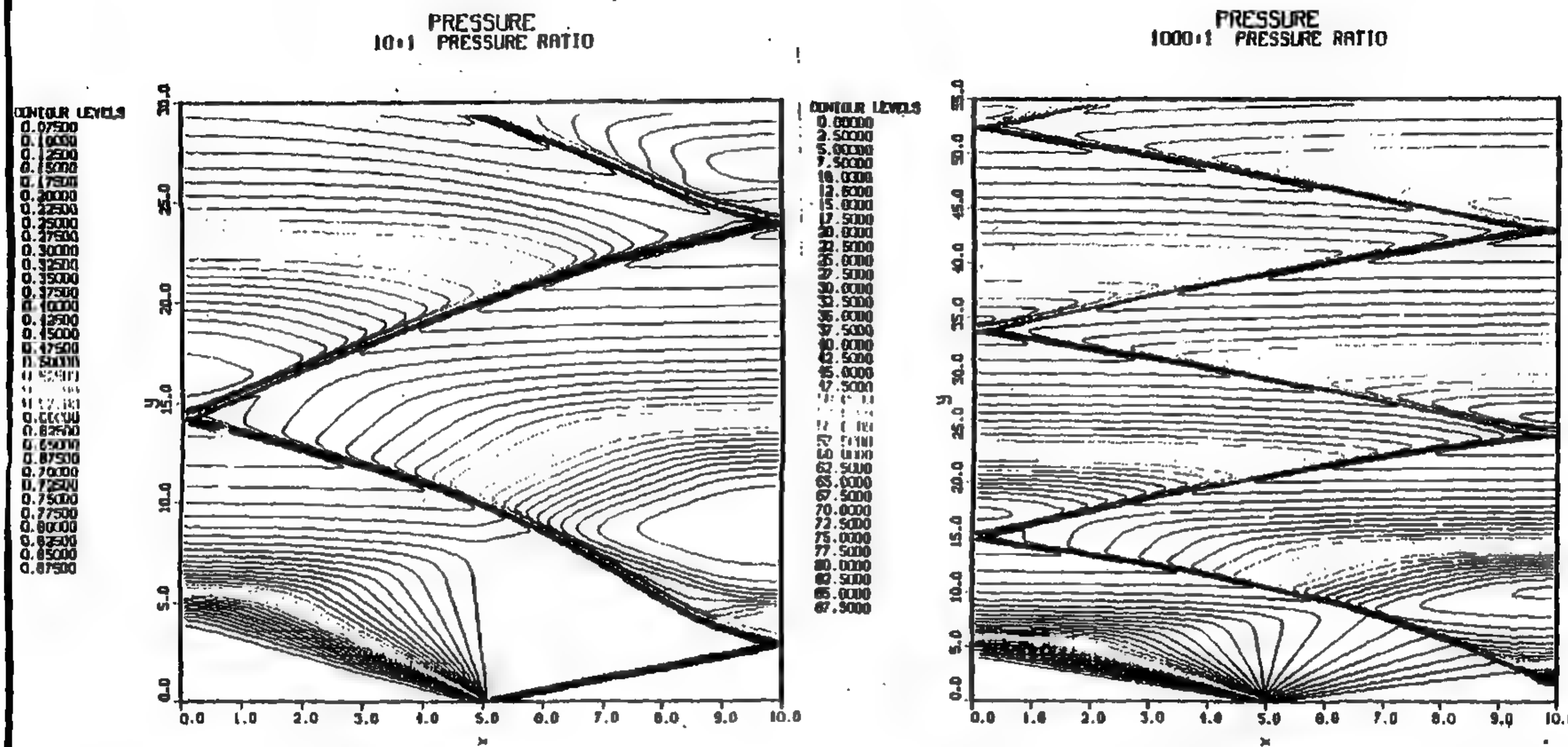
SAIC • An Employee-Owned Company
Science Applications International Corporation

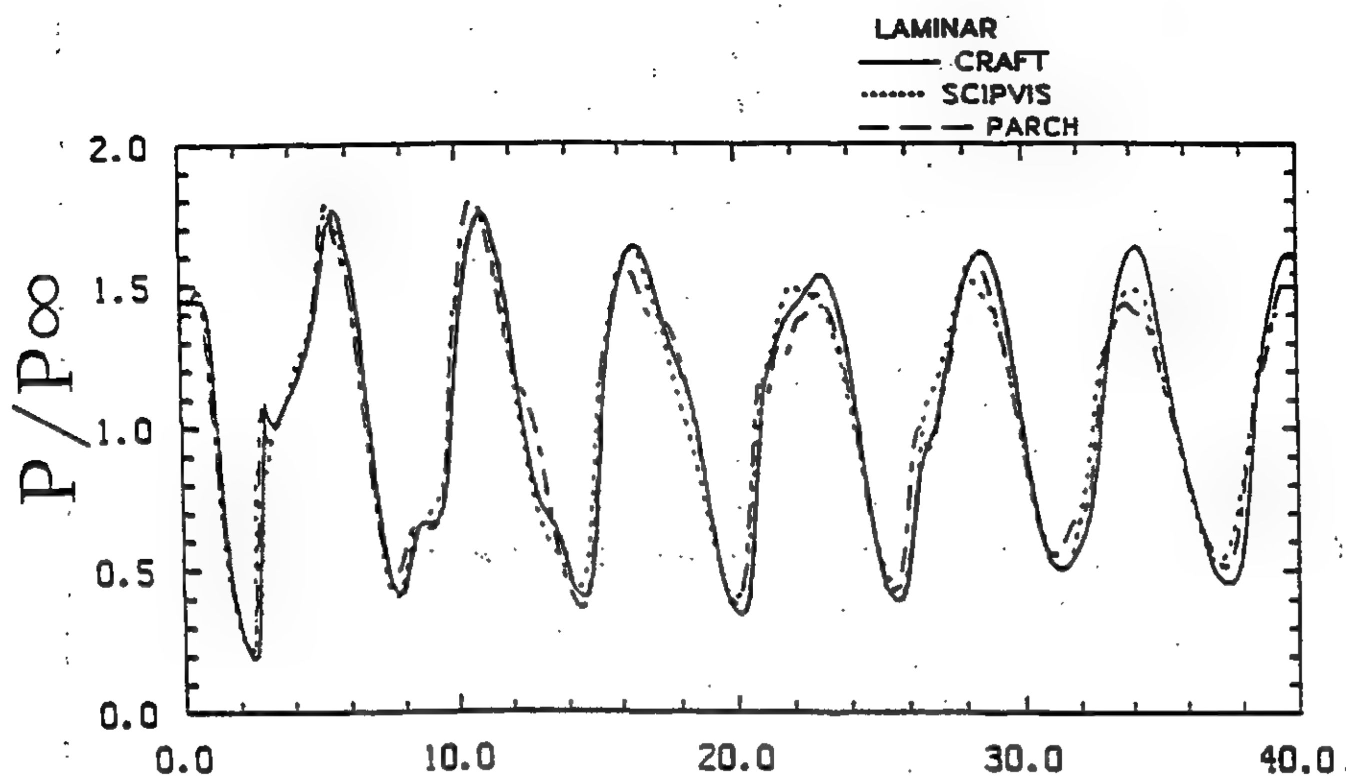
DYNAMIC GRID COMPUTATIONS

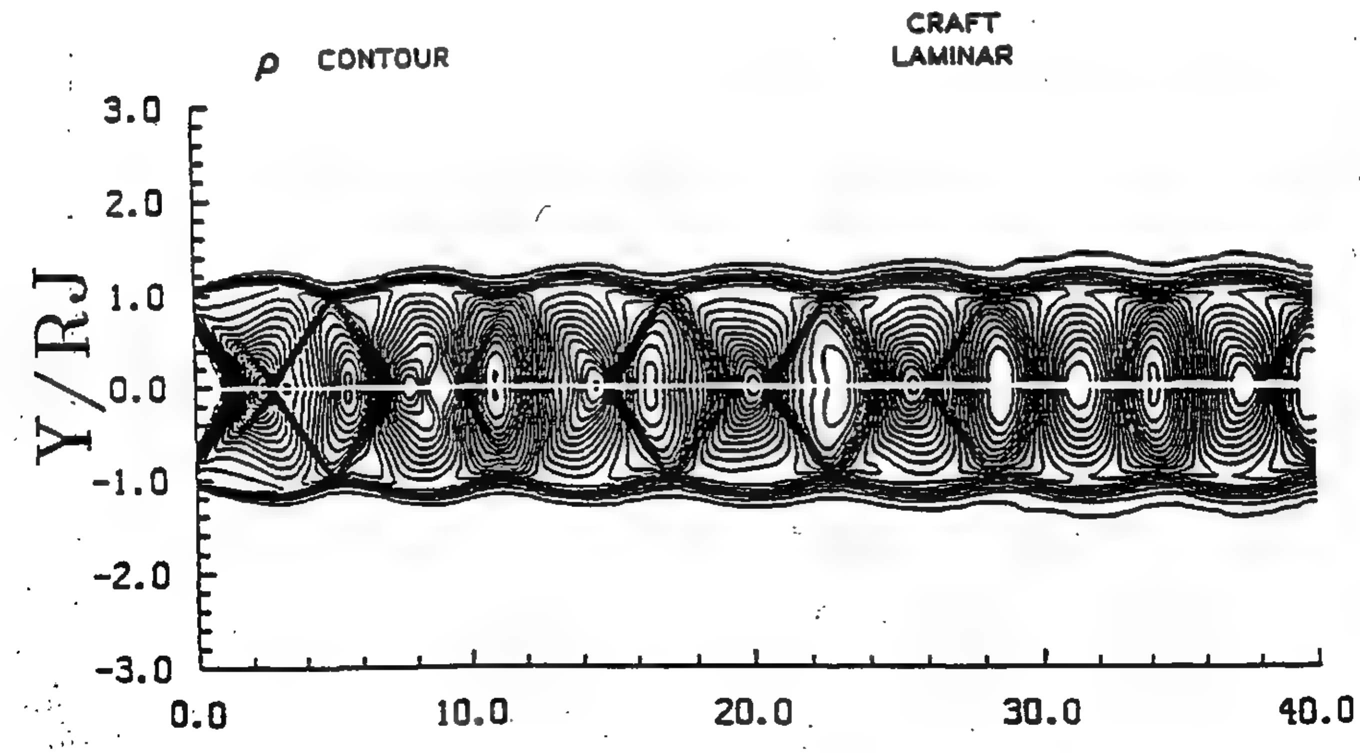
EQUATIONS	$\int_{t_2} Q\,dv - \int_{t_1} Q\,dv + \int_{t_1}^{t_2}\oint_{S(t)} \vec{n}\cdot\vec{f}\,dsdt = \int_{t_1}^{t_2}\int_{V(t)} pdvbdt$ Term I Term II Term III **Term I:** PRIMARY CONSERVED VARIABLES **Term II:** FLUX TERMS **Term III:** SOURCE TERMS **V(t):** TIME VARYING VOLUME
METHODOLOGY	**TREAT GRID AS PURELY GEOMETRIC QUANTITY, i.e., DEFINITION OF CONTRAVARIANT VELOCITY UNCHANGED** **EVALUATE FLUX TERM BY ASSUMING GRID IS HELD CONSTANT AT TIME-AVERAGED VALUE** **EVALUATE SOURCE TERM FOR THE GRID AT THE NEW TIME LEVEL, THUS GIVING:** $\left(\frac{Q^{n+1} - Q^{n}}{\Delta t}\right)V^{n+1} + Q^{n}\left(\frac{V_{n+1} - V^{n}}{\Delta t}\right) + F_n^{n+1}\bar{S}\Delta t = \rho^{n+}V^{n+1}$ $F_n = \vec{n}\cdot\vec{F}$, and $\bar{S}$ is the time averaged metric
NUMERICS	• SPECIFY GRID MOVEMENT AS A FUNCTION OF TIME • EVALUATE F_n AS A THIRD-ORDER UPWIND BASE FLUX • SOLVE LINEARIZED IMPLICIT OPERATOR USING ADI PROCEDURE • USE NEWTON ITERATION FOR HIGHER ORDER ACCURACY IN TIME

SAIC • An Employee-Owned Company
Science Applications International Corporation

SHOCK TUBE COMPUTATIONS – PRESSURE VARIATIONS



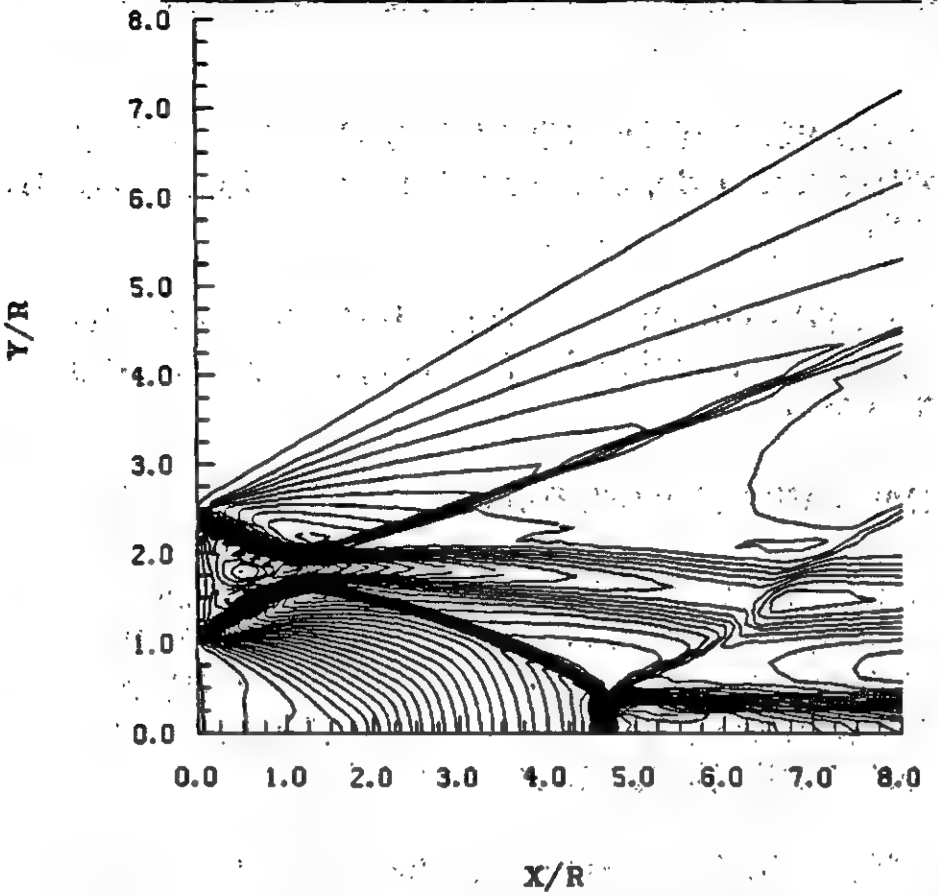

LAMINAR
CRAFT
SCIPVIS
PARCH
P/P∞
2.0
1.5
1.0
0.5
0.0
0.0
10.0
20.0
30.0
40.0


CRAFT
LAMINAR
ρ CONTOUR
Y/RJ
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
0.0
10.0
20.0
30.0
40.0

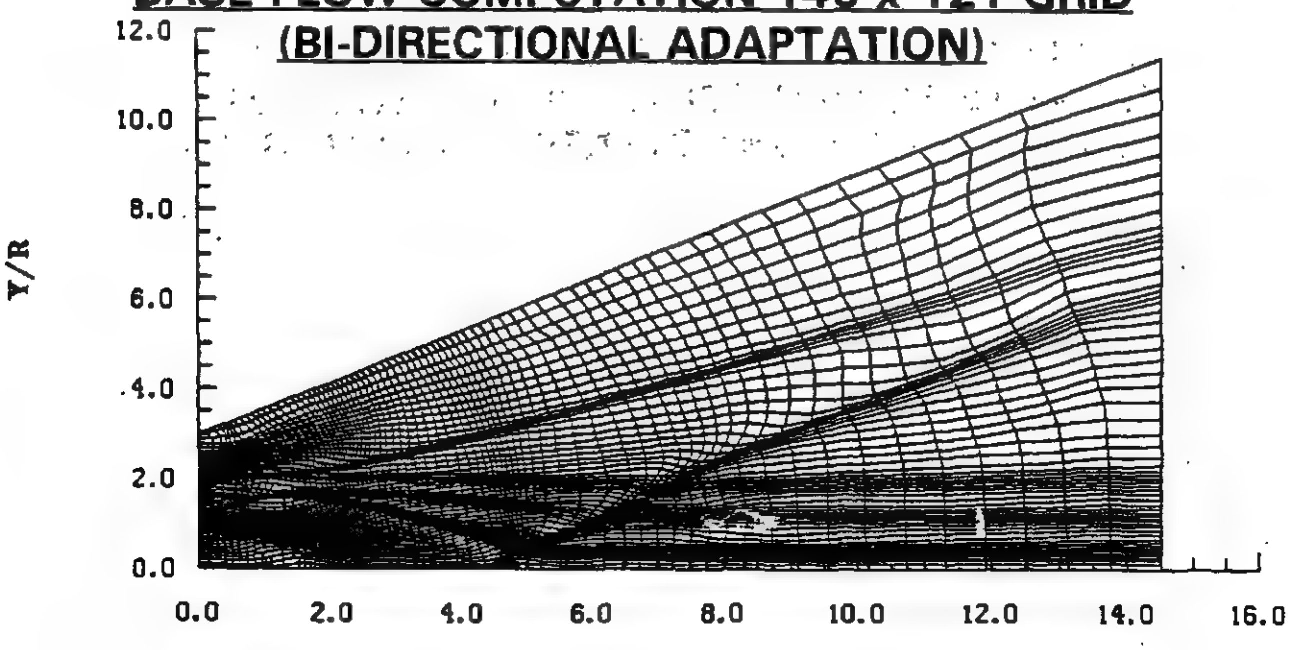
SOLUTION ADAPTIVE GRID GENERATION

- NASA/AMES RESEARCH CENTER SAGE 2D/3D CODE "A Simplified Self-Adaptive Grid Method, SAGE," NASA TM-102198.
- MODIFIED VERSION OF TECHNIQUE DEVELOPED BY Diewert and Nakahashi of NASA/AMES (AIAA PAPER 85-1525, 1985)
- BASED ON VARIATIONAL PRINCIPLES
- PROCEDURE ANALOGOUS TO APPLICATION OF TENSION AND TORSION SPRING FORCES PROPORTIONAL TO LOCAL FLOW GRADIENT AND FINDING EQUILIBRIUM (REDISTRIBUTED) POSITION OF THE RESULTING SYSTEM OF GRID POINTS
- USER-DEFINED WEIGHTED COMBINATION OF ADAPTION VARIABLES
- CURRENTLY SAGE BEING OPTIMIZED FOR ETC PROBLEMS TO YIELD "BEST" COMBINATION OF ORTHOGONALITY, SMOOTHNESS AND CLUSTERING

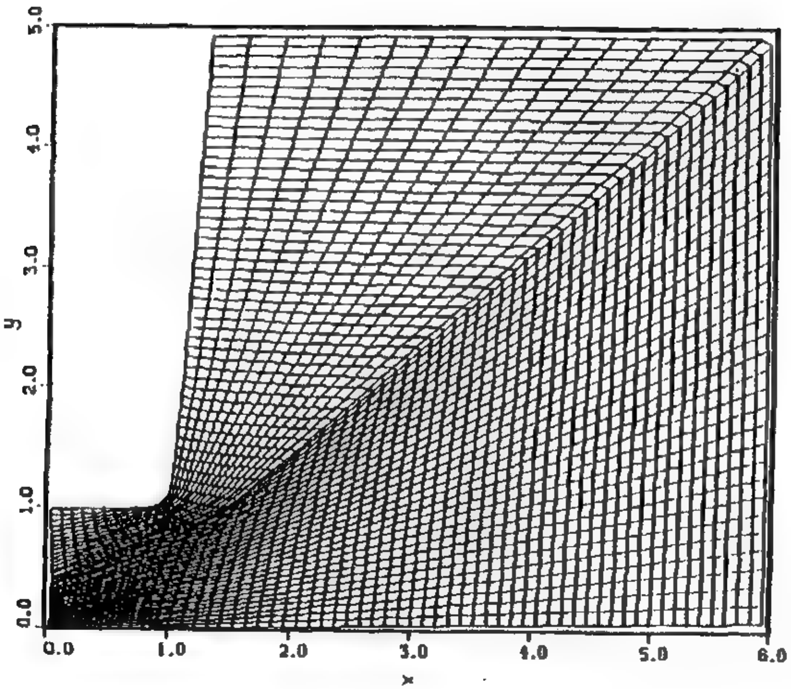
REID AND HASTINGS
BASE MACH NUMBER CONTOURS

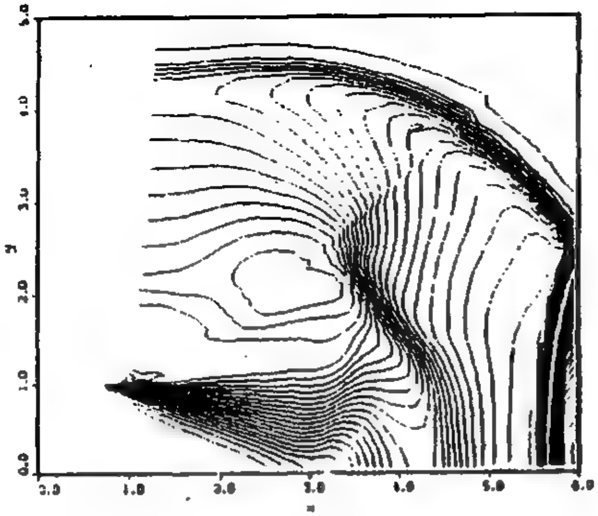


BASE FLOW COMPUTATION 145 x 121 GRID
(BI-DIRECTIONAL ADAPTATION)

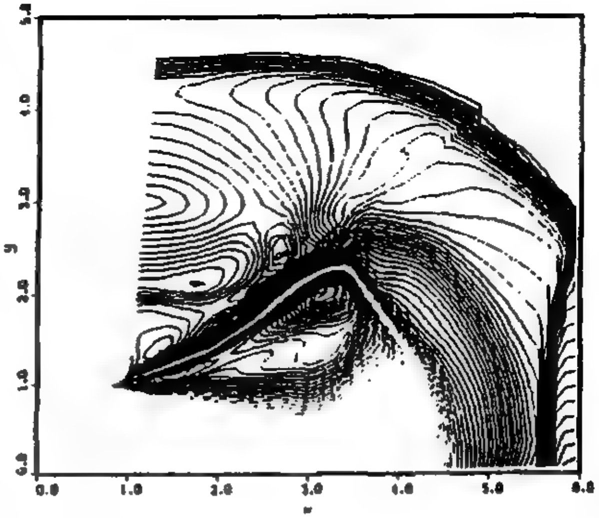


TRANSIENT UNDEREXPANDED JET INJECTION INTO MIXING CHAMBER
INITIAL PRESSURE RATIO = 5

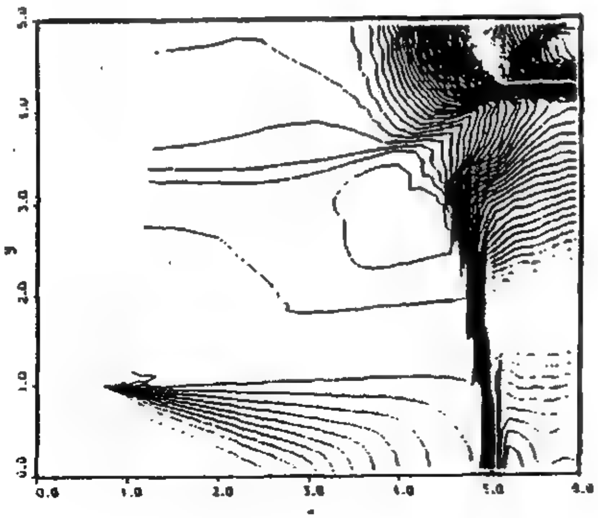




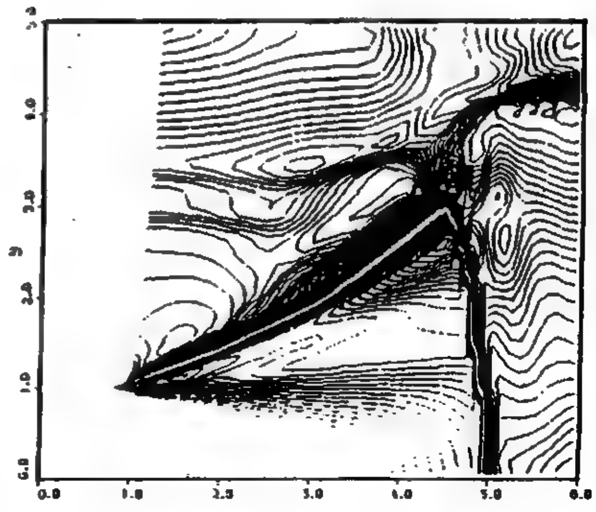
a) Pressure



b) Mach Number



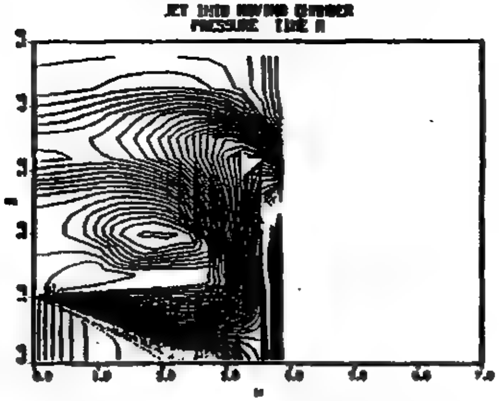
a) Pressure

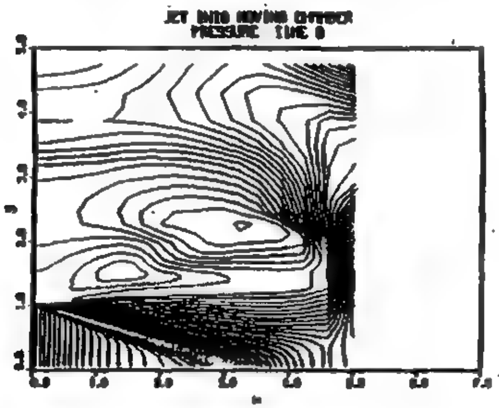


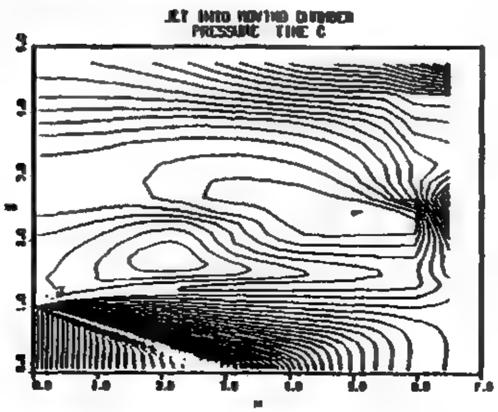
b) Mach Number

JET INTO CHAMBER WITH MOVING WALLS

PRESSURE SNAPSHOTS





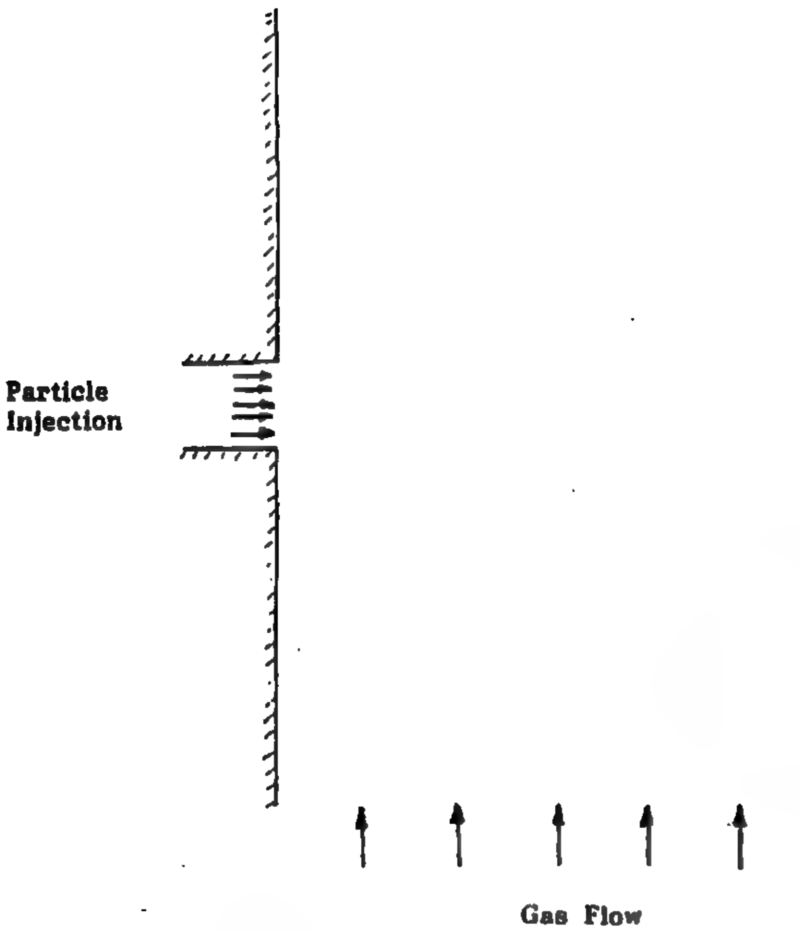


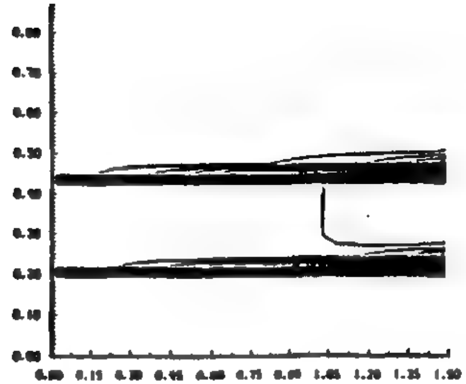
SAIC An Employee-Owned Company
Science Applications International Corporation

FEATURES OF THE PARTICLE-CLOUD SOLVER

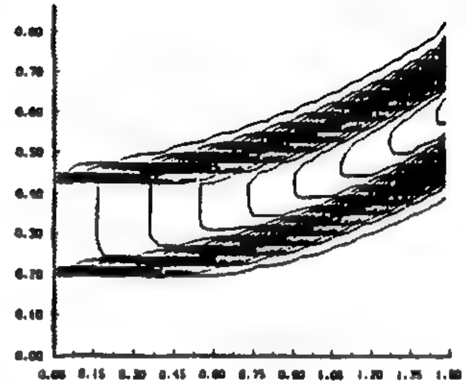
FEATURES	PARTICLE CLOUD SOLVER
EQUATIONS	• 1D/2D/3D TIME MARCHING PARTICLE-CLOUD EQUATIONS • FULLY COUPLED PARTICLE DENSITY, VELOCITY, AND TEMPERATURE EQUATIONS • DRAG TERMS MODELED FOR NON-EQUILIBRIUM PARTICLE INTERACTIONS • DRAG RELATIONS OF HERMSEN AND HENDERSON AVAILABLE • PHASE CHANGE OF PARTICLES INCORPORATED
NUMERICS	• LIMITING PARTICLE STREAMLINE CAPTURED AS A DISCONTINUITY IN THE PARTICLE-CLOUD DENSITY • ROE TVD UPWIND ALGORITHM FULLY CONSISTENT WITH GAS PHASE NUMERICS • IMPLICIT TREATMENT OF PARTICLE SOURCE AND FLUX TERMS • ADI BLOCK INVERSION • TIME ACCURATE/TIME ASYMPTOTIC NUMERICS • NEWTON ITERATION TO REMOVE APPROXIMATE FACTORIZATION ERRORS
BOUNDARY CONDITIONS	• WALL WITH PARTICLES STICKING • WALL WITH PARTICLES SLIPPING • INFLOW • OUTFLOW

SAIC An Employee-Owned Company
Science Applications International Corporation

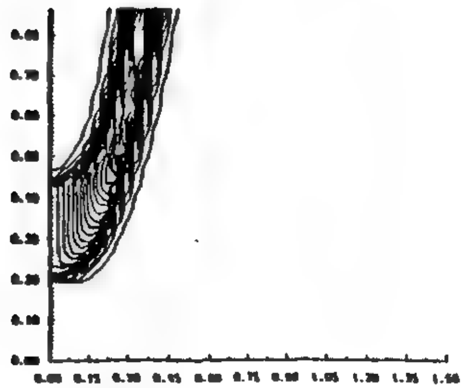




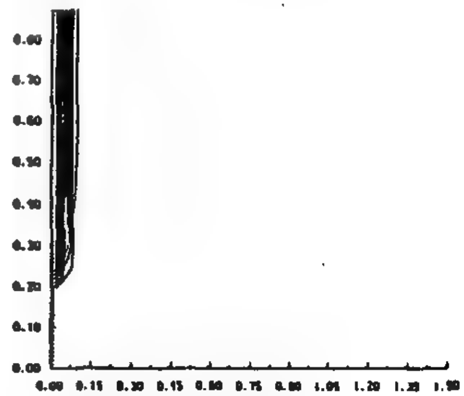
(a) 600μm Case



(b) 60μm Case

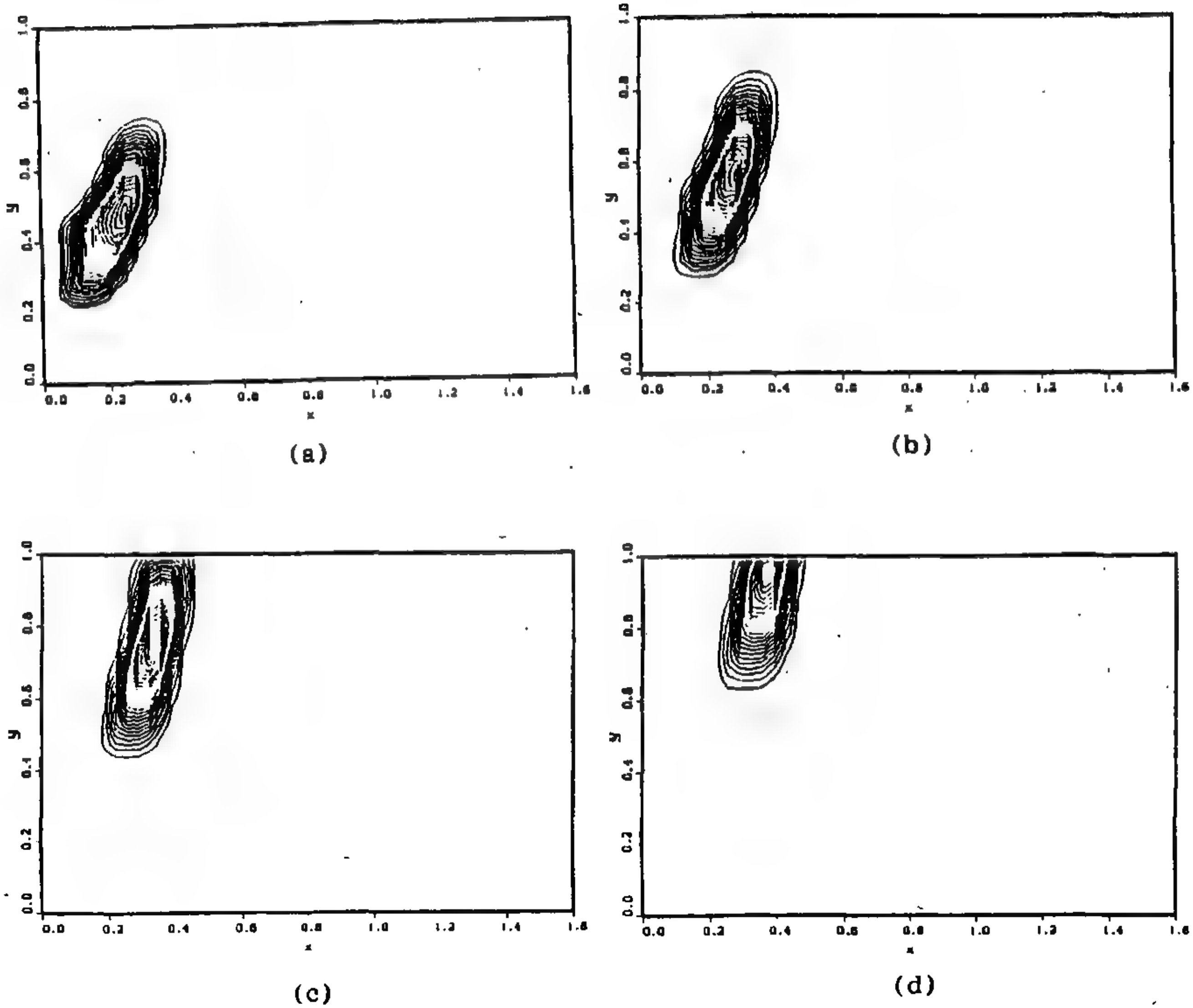


(c) 6μm Case

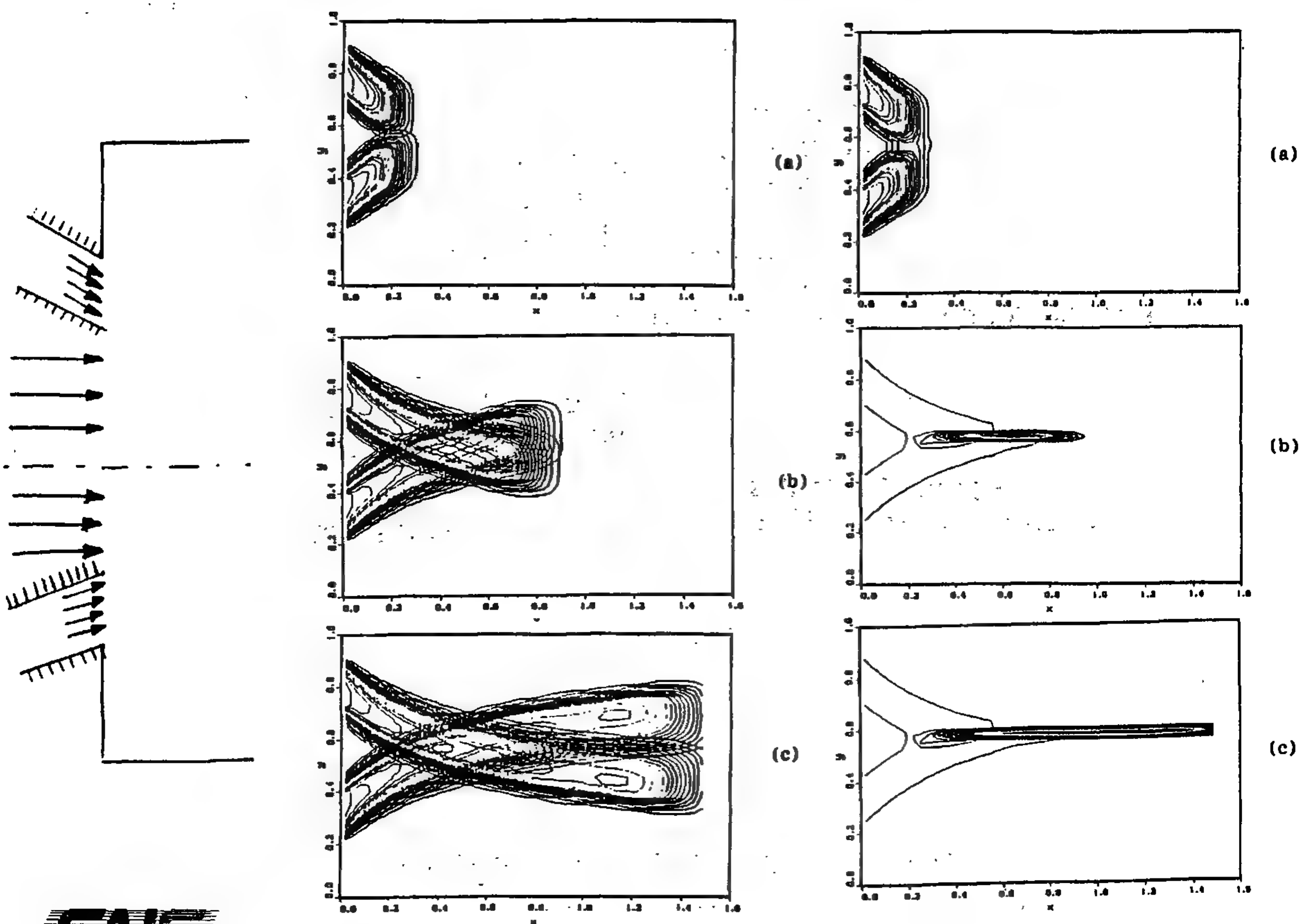


(d) .6μm Case

6μm Finite-Duration Transverse Particle Injection: Density Contours of Particle Packet at Four Time Intervals

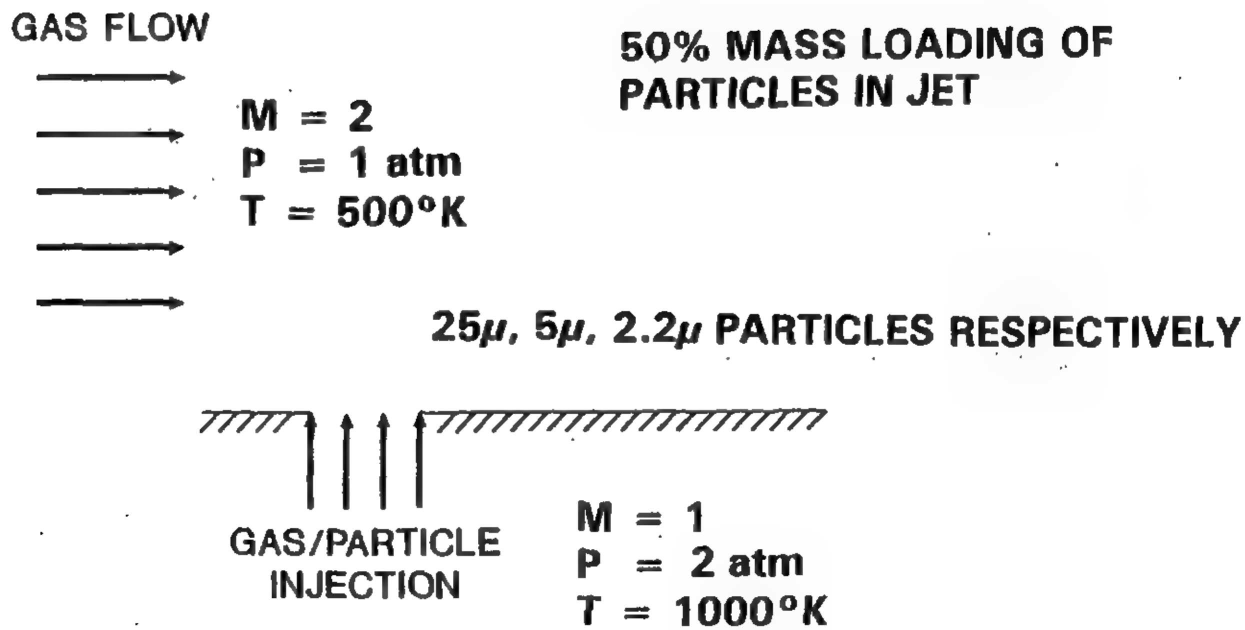


(a) (b) (c) (d)



Science Applications International Corporation
An Employee-Owned Company

MULTI-PHASE PERPENDICULAR JET INJECTION
PARAMETRIC VARIATION OF PARTICLE-SIZE



BUILDING-BLOCK APPROACH FOR ETC GUN SIMULATION

1. NUMERICAL STUDIES WITH EXISTING VERSION OF CRAFT

   - PLASMA JET-WORKING FLUID INTERACTIONS
     : GRID DYNAMICS/ADAPTIVE GRIDDING
     : THERMOCHEMICAL EFFECTS
     : BL/WALL TEMPERATURES
     : INJECTOR EFFECTS/SINGLE vs MULTIPLE
     : STRONGLY-COUPLED PROJECTILE SOLUTION

2. NEAR-TERM UPGRADES

   - COMPLEX EQUATIONS OF STATE → Roe/TVD [RESEARCH]
   - VOLUMETRIC EFFECTS/DROPLETS
   - INTERIOR BALLISTIC/CAPILLARY COUPLING
   - DROPLET FORMATION/COMBUSTION
   - RADIATIVE EFFECTS

3. PHENOMENOLOGICAL STUDIES

   - HOMOGENOUS vs NON-HOMOGENOUS MIXTURE ASSUMPTIONS
   - COMBUSTION CHEMISTRY-SIMPLIFIED vs MULTI-STEP REPRESENTATION
   - MIXING/PENETRATION OF PLASMA JET- $k\epsilon$ vs LES TURBULENCE MODELING

•
•
•

EQUATION OF STATE (EOS) AND CHARACTERISTIC-BASED UPWIND SCHEMES

- RIEMANN SOLVER (Roe/TVD, Godunov, etc.) ORIGINALLY FORMULATED FOR IDEAL GAS DYNAMICS
- MORE RECENTLY, ADVANCES FOR MULTI-COMPONENT, REAL GAS FLOWS WITH CHEMICAL NONEQUILIBRIUM (Vinokur, Liu – 1988-89)
- ETC FLOWFIELDS CHARACTERIZED BY VERY COMPLEX EOS WITH COMPLICATED CONSTITUTIVE MODELING, PHASE CHANGES, etc. (NON-CONVEX EOS)
  - EXACT RIEMANN SOLUTION ENTAILS PROHIBITIVE COSTS FOR LARGE-SCALE COMPUTATIONS
  - RECENTLY, EFFICIENT ALTERNATIVE RIEMANN SOLVERS FORMULATED WHICH COMPARE FAVORABLY WITH MORE RIGOROUS GODUNOV SCHEME

GODUNOV BASED RIEMANN SOLVER

Collins, P. and Glaz, H.M., "Efficient Solution Algorithms for the Riemann Problem for Real Gases," *J. Computat. Physics*, 59 (1985), pp. 264-298.

ALTERNATIVE RIEMANN SOLVERS

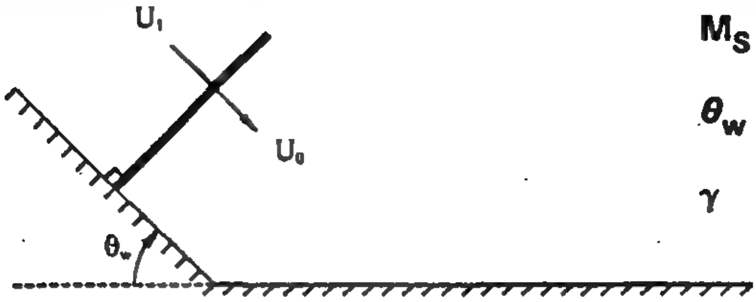
Bell, J.B., Colella, P. and Trangenstein, J.A., "Higher-Order Godunov Methods for General Systems of Hyperbolic Conservation Laws, *J. Computat. Physics*, 82 (1989), pp. 362-397.

Davis, S.F., "Simplified Second-Order Godunov Type Methods," SIAM *J. Sci. Statit. Comput.*, 9 (1988) pp. 445-473.

Harten, A. Lax, P.D., and van-Leer, B., "On Upstream Differencing and Godunov-type Schemes for Hyperbolic Conservation Laws, SIAM, Rev., 25 (1983) pp. 35-61.

FLOW STRUCTURE / EOS

OBLIQUE SELF-SIMILAR SHOCK REFLECTION

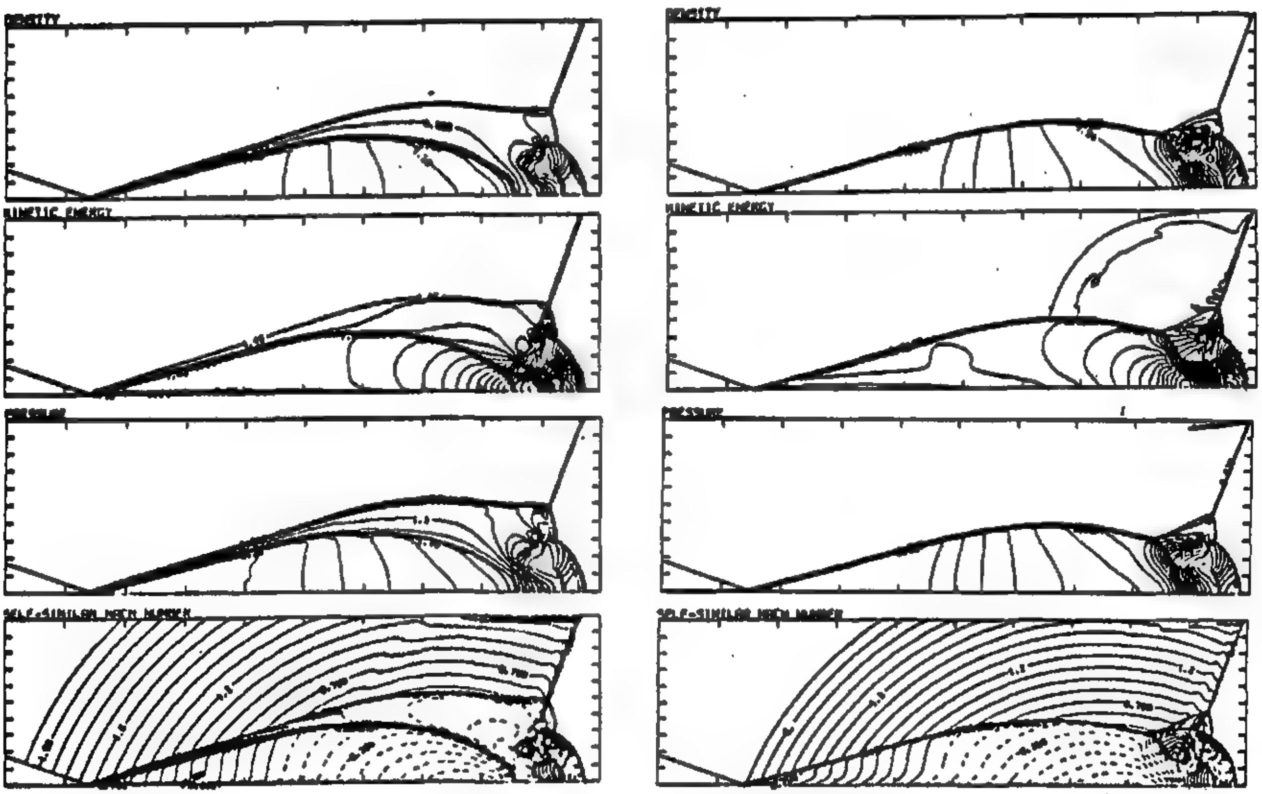


$M_S = 5.7$

$\theta_w = 20°$

$\gamma = 1.4$

Figure 1. Schematic diagram for flowfield initialization.



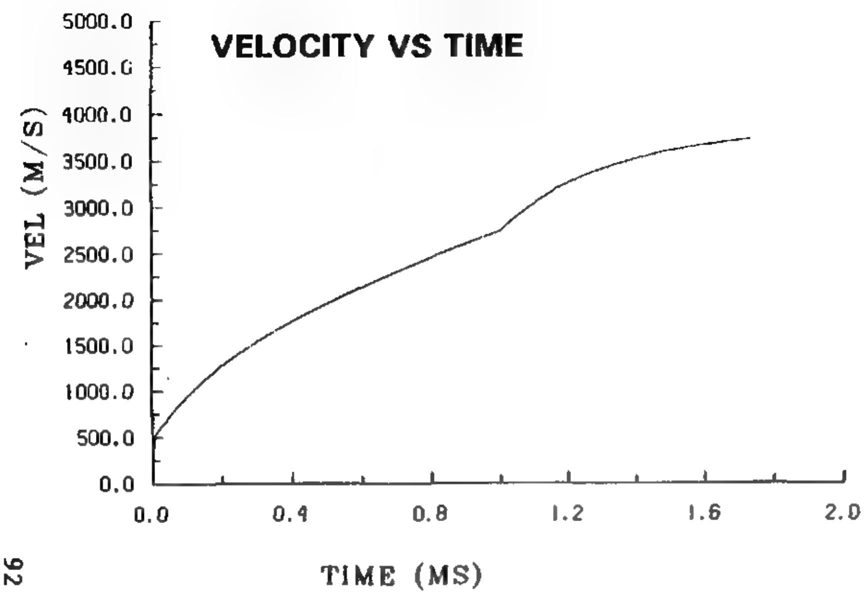
(a) (b)

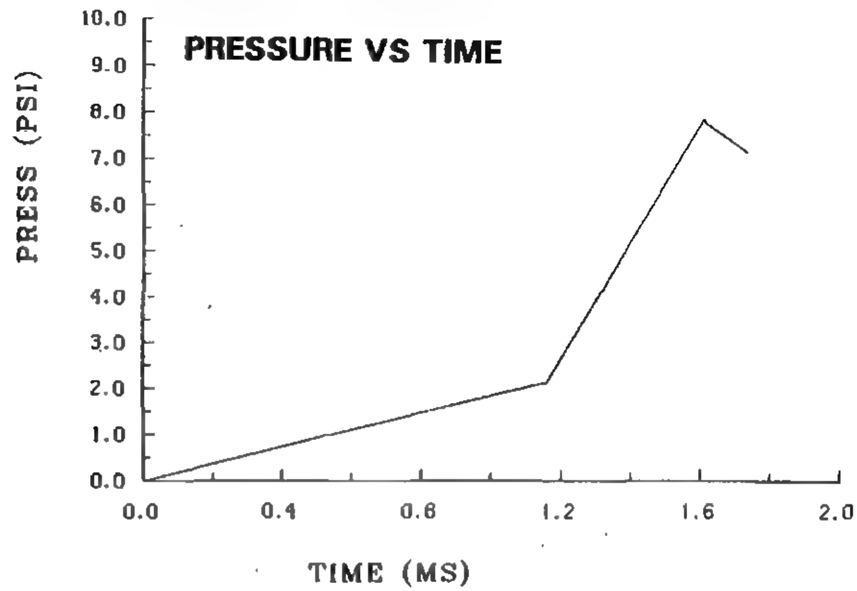
NON-CONVEX EOS	CONVEX EOS
MODIFIED POLYTROPIC	POLYTROPIC
$p = V^{-\gamma} + f(v)$ (PHASE CHANGE)	$p = V^{-\gamma}$

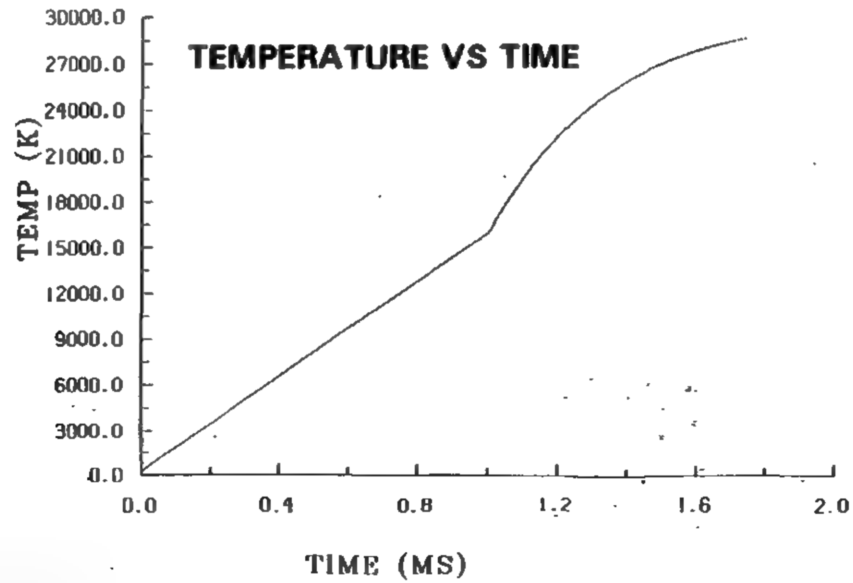
2D Greenfarm Simulation

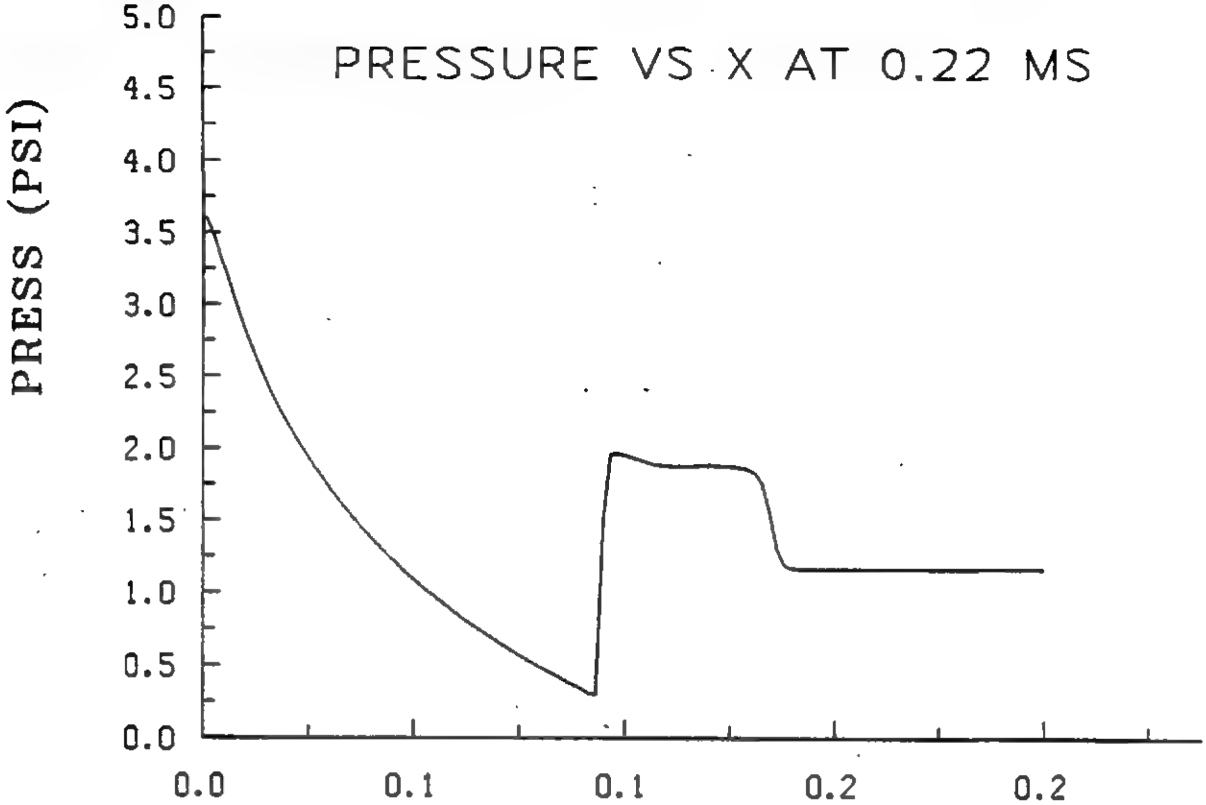
- 120mm
- Experimental data exhibits pressure waves

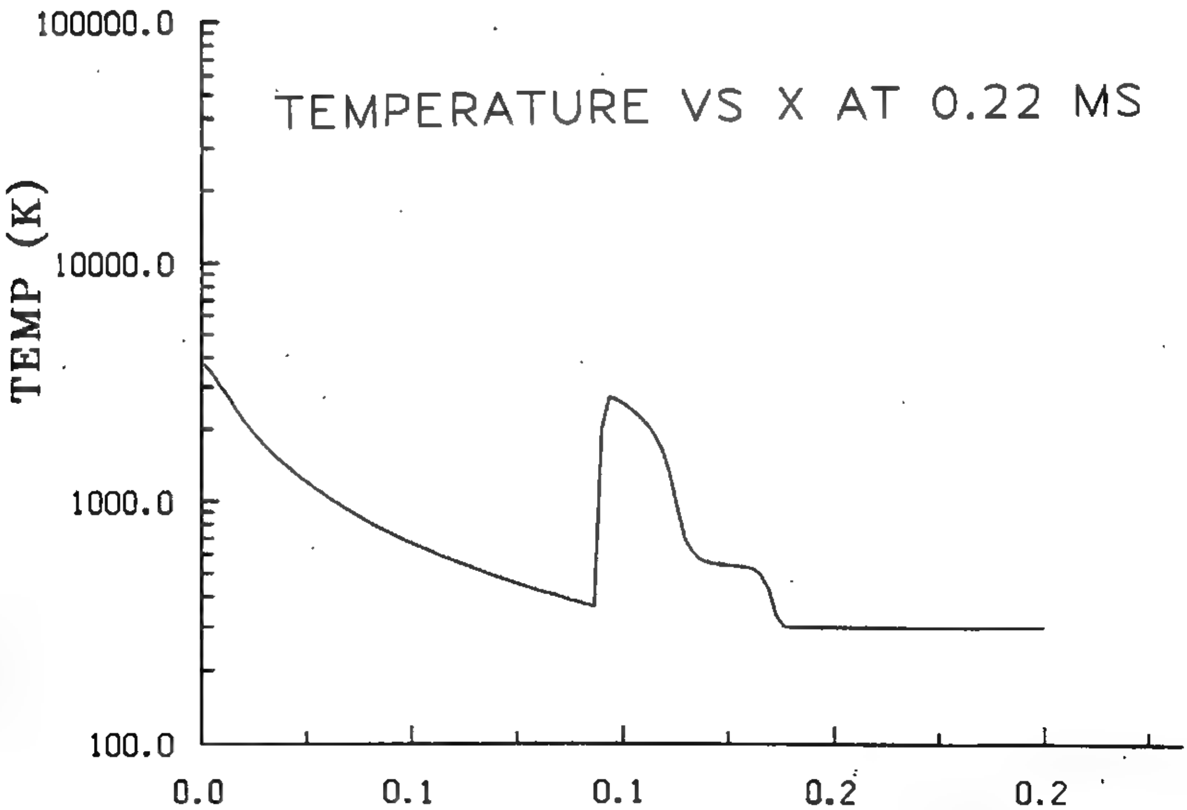
INFLOW FOR GREEN FARM SIMULATION

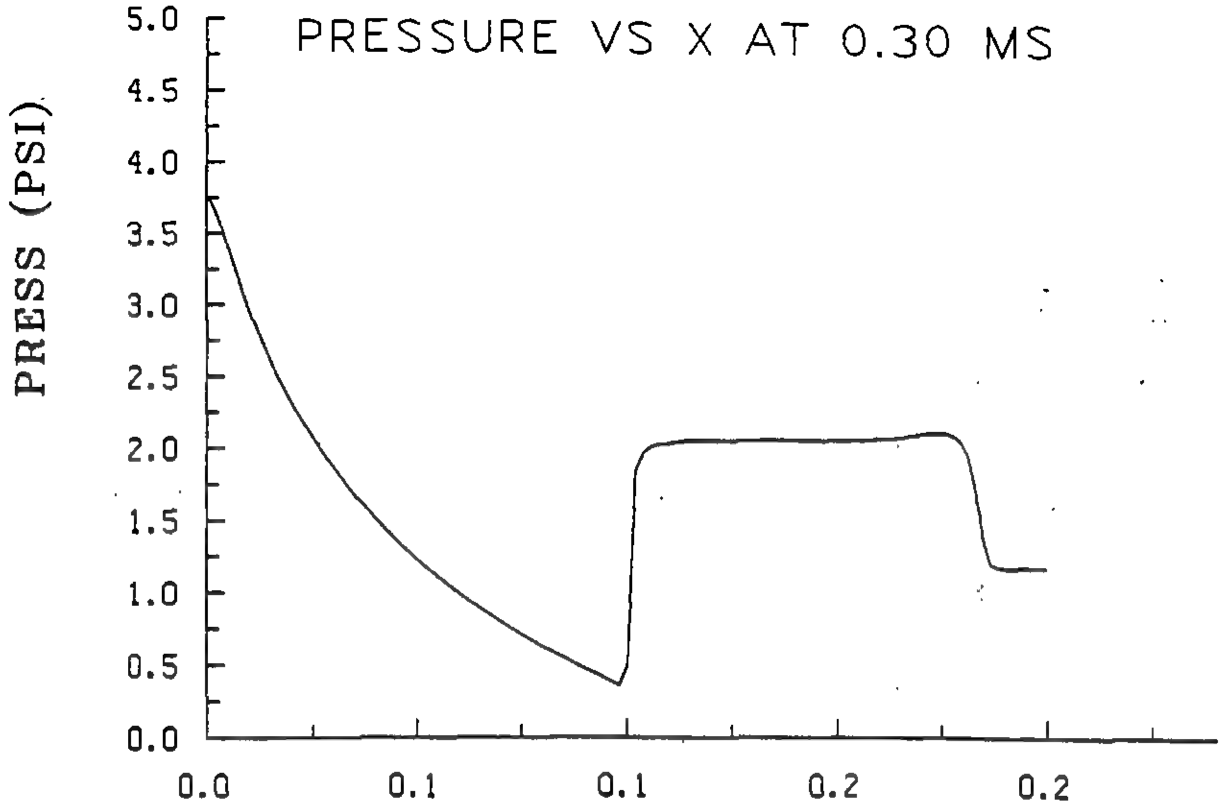


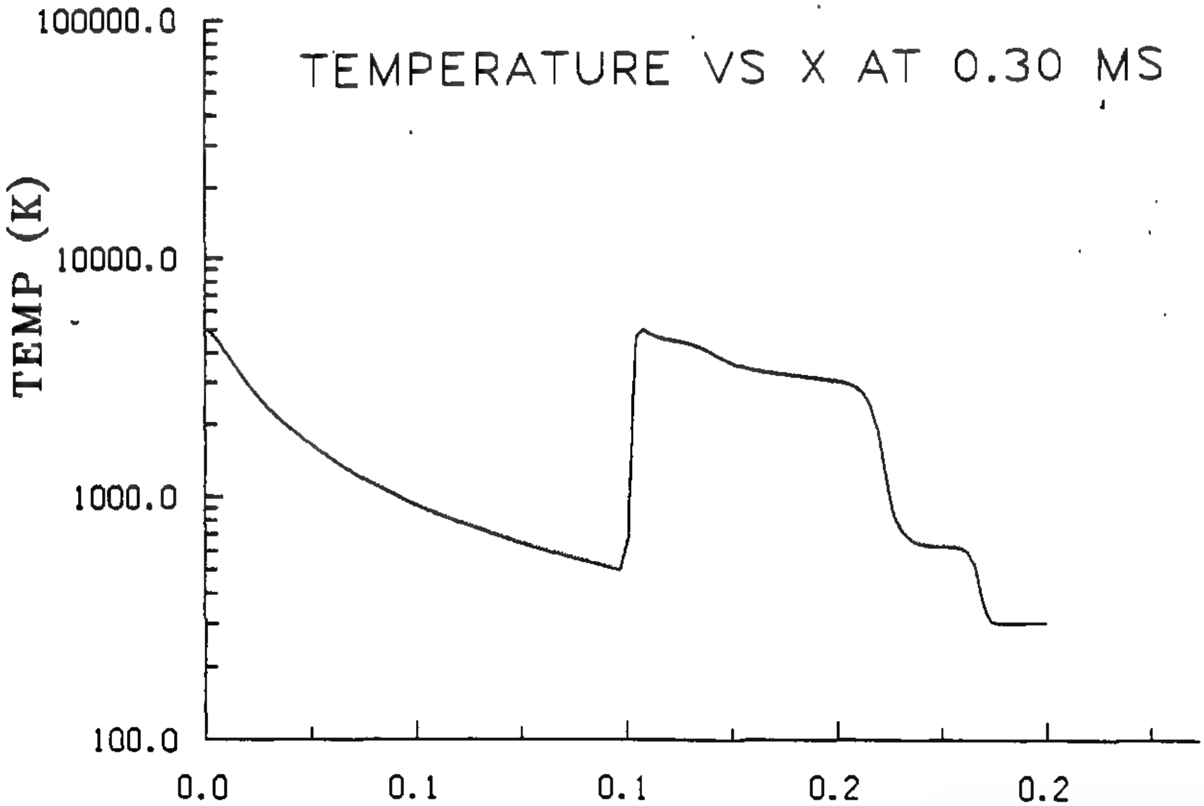


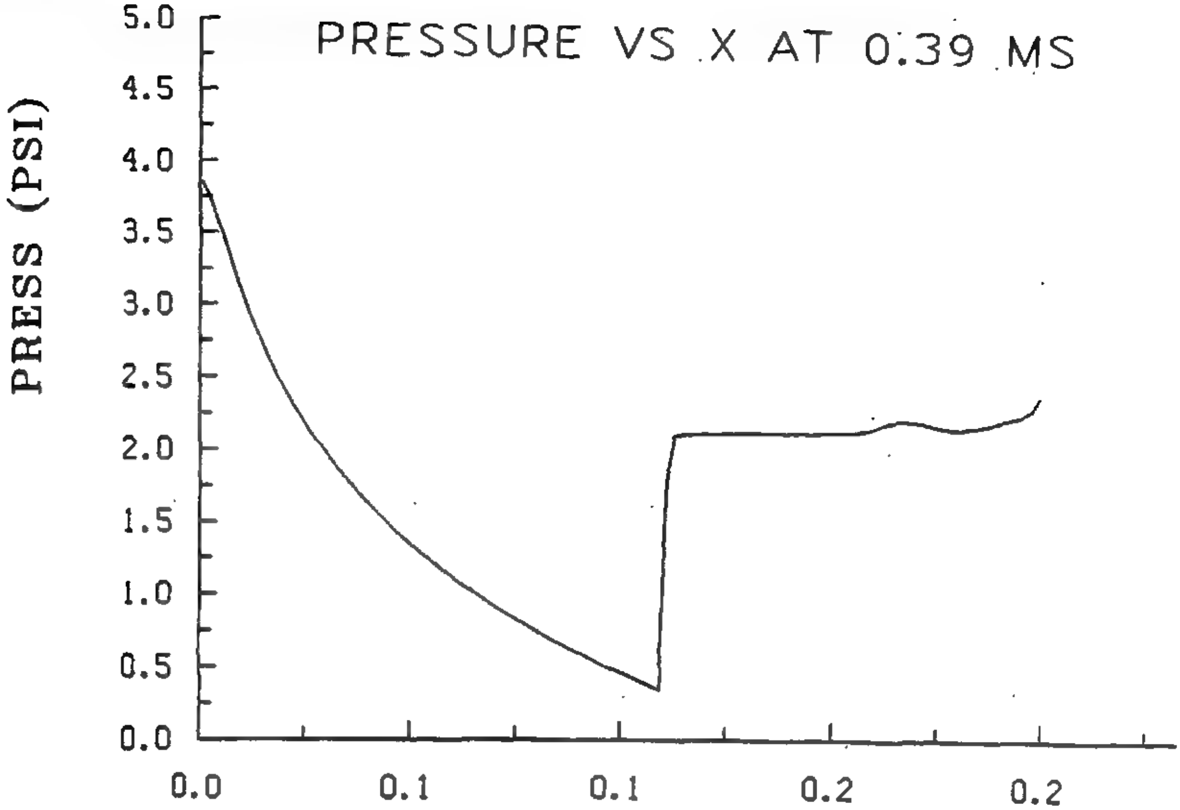


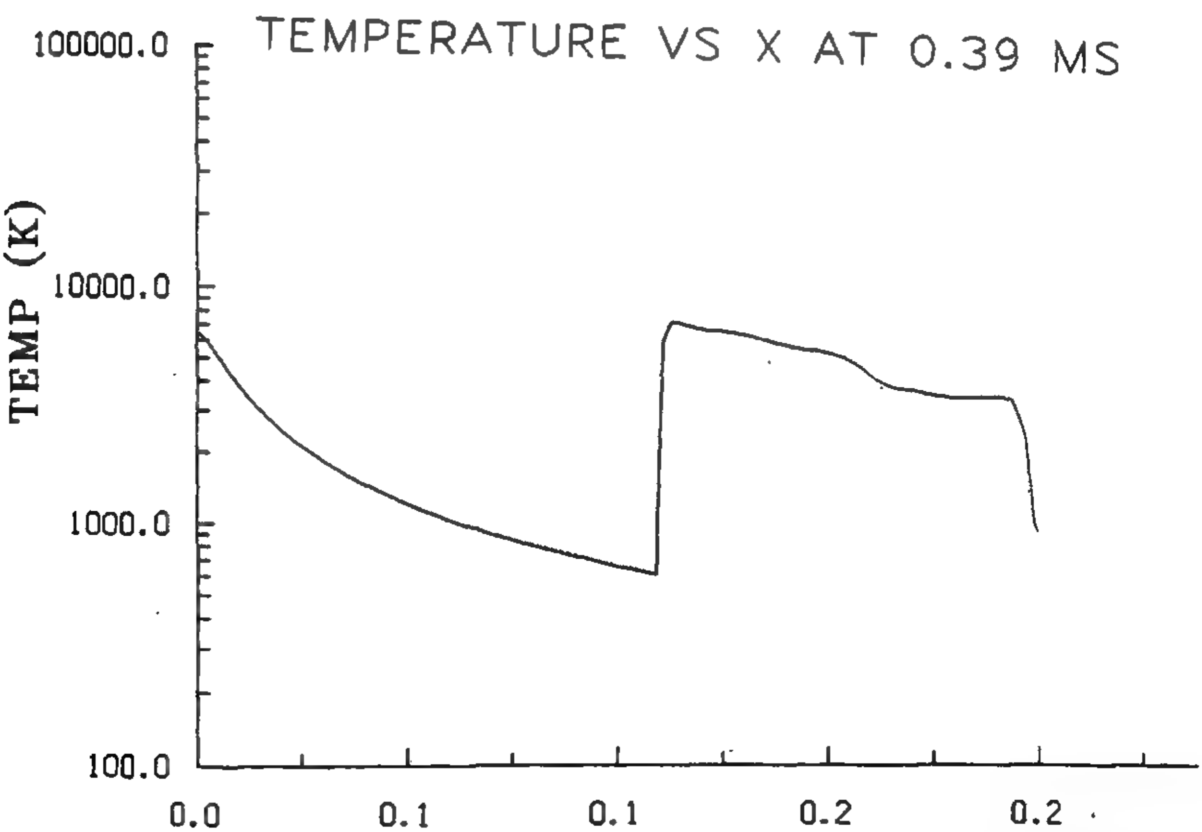

PRESSURE VS X AT 0.22 MS
PRESS (PSI)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.1
0.1
0.2
0.2

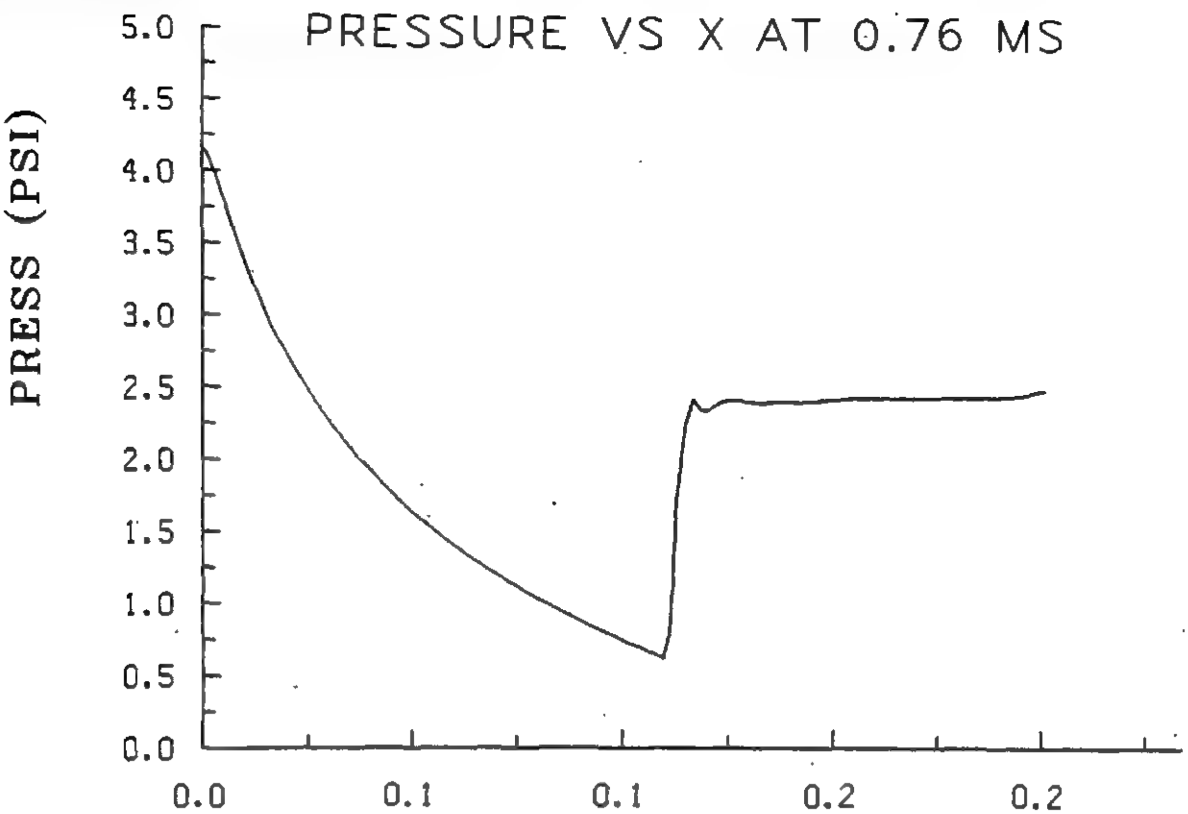

TEMPERATURE VS X AT 0.22 MS
TEMP (K)
100000.0
10000.0
1000.0
100.0
0.0
0.1
0.1
0.2
0.2

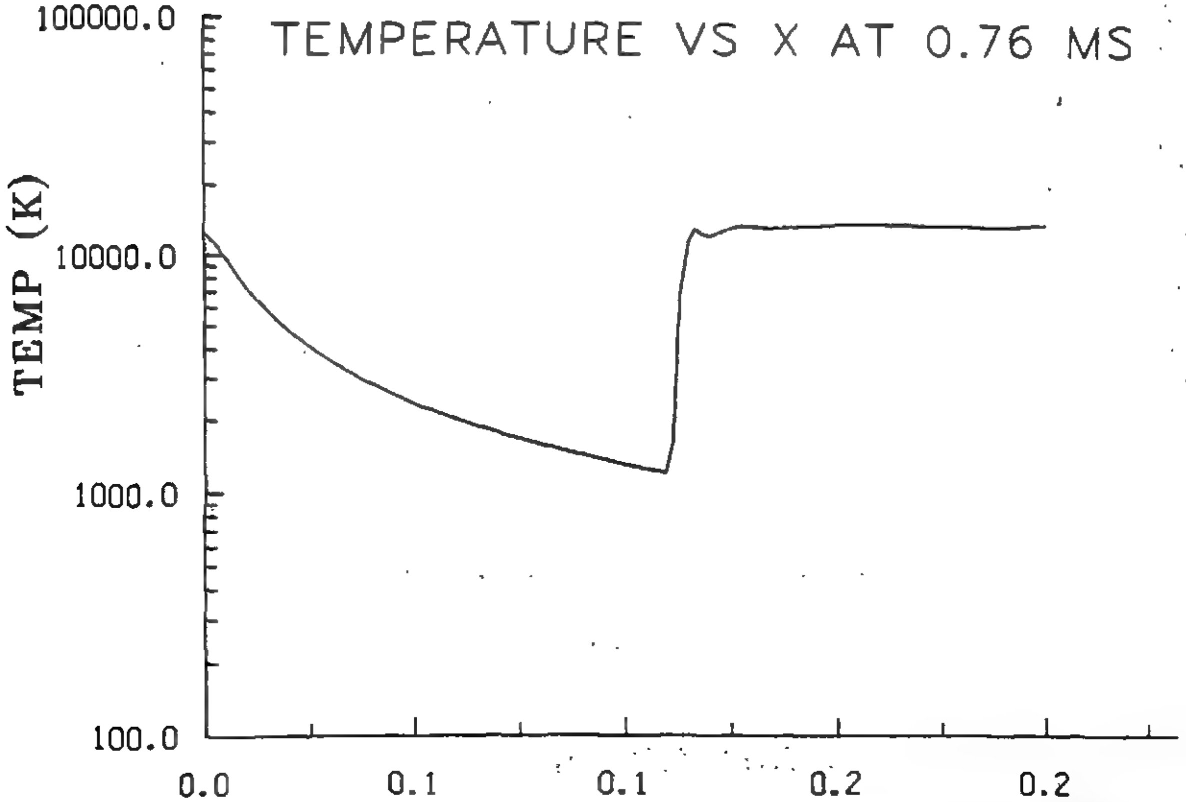

PRESSURE VS X AT 0.30 MS
PRESS (PSI)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.1
0.1
0.2
0.2


TEMPERATURE VS X AT 0.30 MS
TEMP (K)
100000.0
10000.0
1000.0
100.0
0.0
0.1
0.1
0.2
0.2

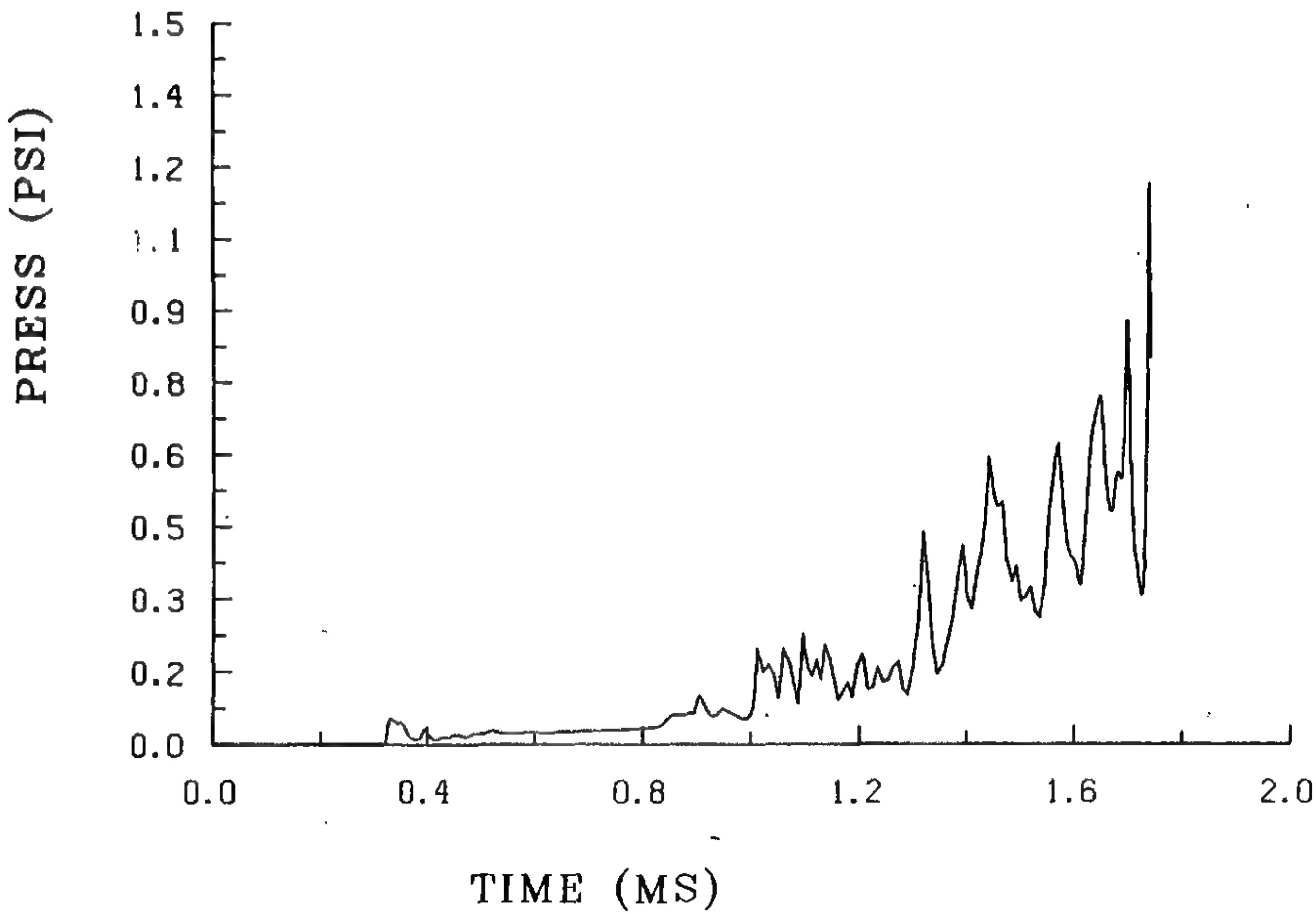

PRESSURE VS X AT 0.39 MS
PRESS (PSI)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.1
0.1
0.2
0.2

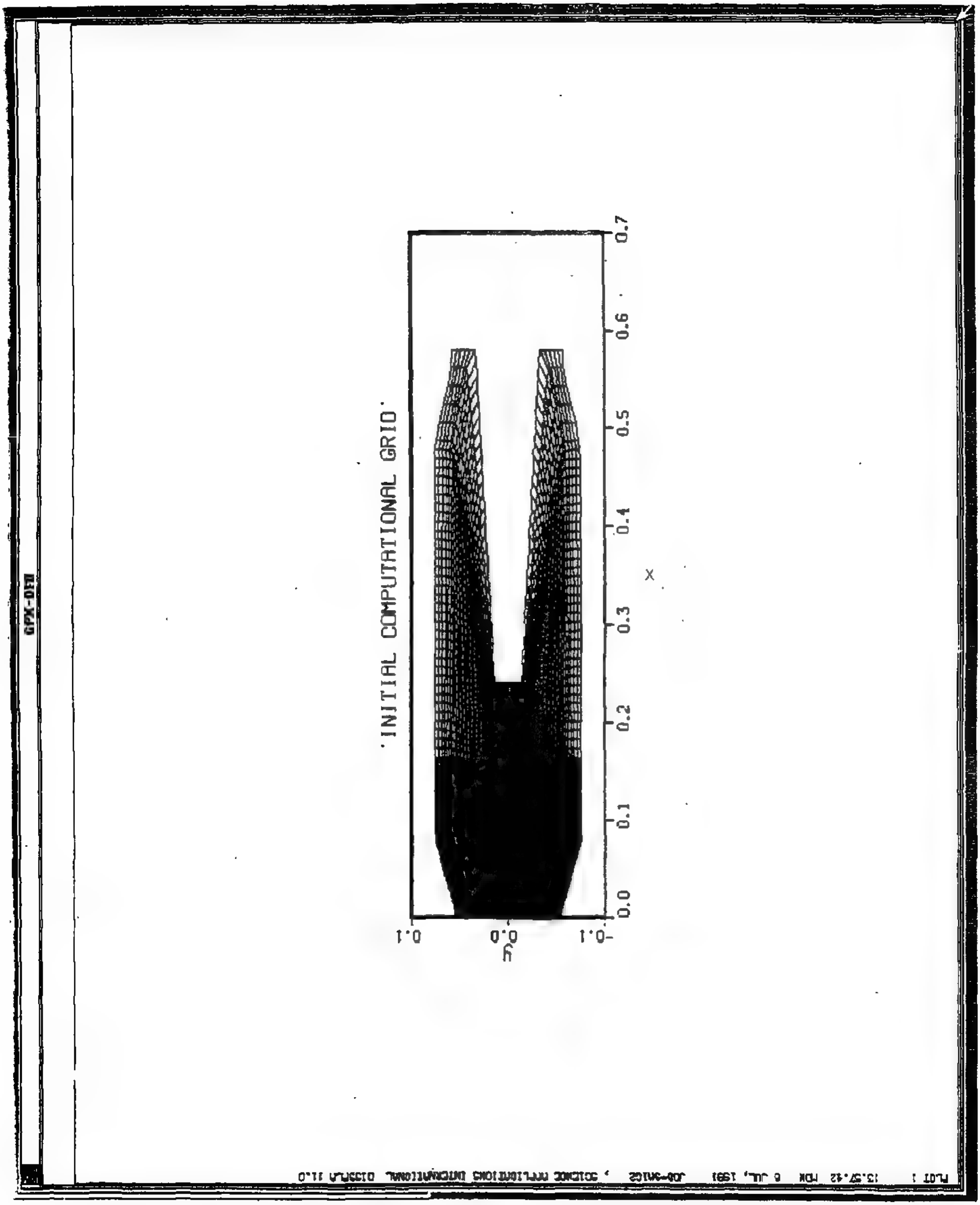

TEMPERATURE VS X AT 0.39 MS
TEMP (K)
100000.0
10000.0
1000.0
100.0
0.0
0.1
0.1
0.2
0.2


PRESSURE VS X AT 0.76 MS
PRESS (PSI)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.1
0.1
0.2
0.2


TEMPERATURE VS X AT 0.76 MS
TEMP (K)
100000.0
10000.0
1000.0
100.0
0.0
0.1
0.1
0.2
0.2

BASE PRESSURE VS TIME




'INITIAL COMPUTATIONAL GRID'
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
x
-0.1
0.0
0.1
y

2D Greenfarm Simulation

- Model provides excellent resolution
- Dynamic gridding & moving projectile
- Pressure waves interact with geometry
- Complicated flow structure

Summary

- CRAFT applicable to ETC flows
  - state-of- the-art numerics
  - synergistic with other DoD & NASA efforts
  - emphasis on first-principles model
  - core model for submodules developed by DoD & DOE labs, university, contractors

- Preliminary application to Greenfarm data
  - excellent resolution of flow structure
  - geometric effects evident
  - pressure waves observed

- Building-block approach
  - plasma-working fluid interaction
  - liquid EOS

RECENT ADVANCES IN CAP_{tm} GUN MODELING

Dave Cook and Jahn Dyvik
FMC Corporation
Minneapolis, MN 55421-1498

ABSTRACT

The FMC Corporation is continuing the effort to develop and adapt ETC interior ballistics models to reflect experimental performance of present gun designs. A new version of a 2-D interior ballistics code with an empirical combustion model has been applied to recently obtained 30-mm data. FMC is also testing alternative propellants in the 30-mm gun, and efforts to describe their thermochemistry and ballistic performance will be discussed.

FMC is currently firing 60-mm ETC guns under contracts to the Navy and DNA, as well as under IR&D. These efforts are testing a number of new cartridge designs. A modeling effort has recently been completed which describes two of these new designs using a variable area, 1-D interior ballistics code. This code contains the same gas generation model as the 2-D code, but includes additional features such as a flexible computational domain and an empirical reaction kinetics model. When these new computational algorithms mature, and cartridge designs are decided, the new 1-D features will be incorporated into the 2-D code.

FMC

Recent Advances in CAP_{tm} Gun Modeling

102

Dave Cook
Jahn Dyvik

FMC

Overview

- Status of 2-D Modeling at FMC
- 1-D Interior Ballistics Code Development
- Recent 1-D Applications at 60-mm
- Impact of 1-D Calculations on Future 2-D Work

Status of 2-D Modeling at FMC

- The 2-D model of the CAP$_{tm}$ process contains three coupled sub-models, a PFN routine, a plasma injector routine, and a 2-D interior ballistics code which solves the viscous Navier-Stokes equations.

- The first version of this code was validated using mostly large caliber data. Recently, the numerics have been changed to a donor cell approach and an artificial diffusion model has been added.

- This new version has been compared to 30-mm ballistics data. Agreement is good, however, some of the details in calculated pressure traces indicate a more complex combustion model is necessary.

Empirical Combustion Model

- Three functions are used to describe the energy released from propellant combustion. They are:

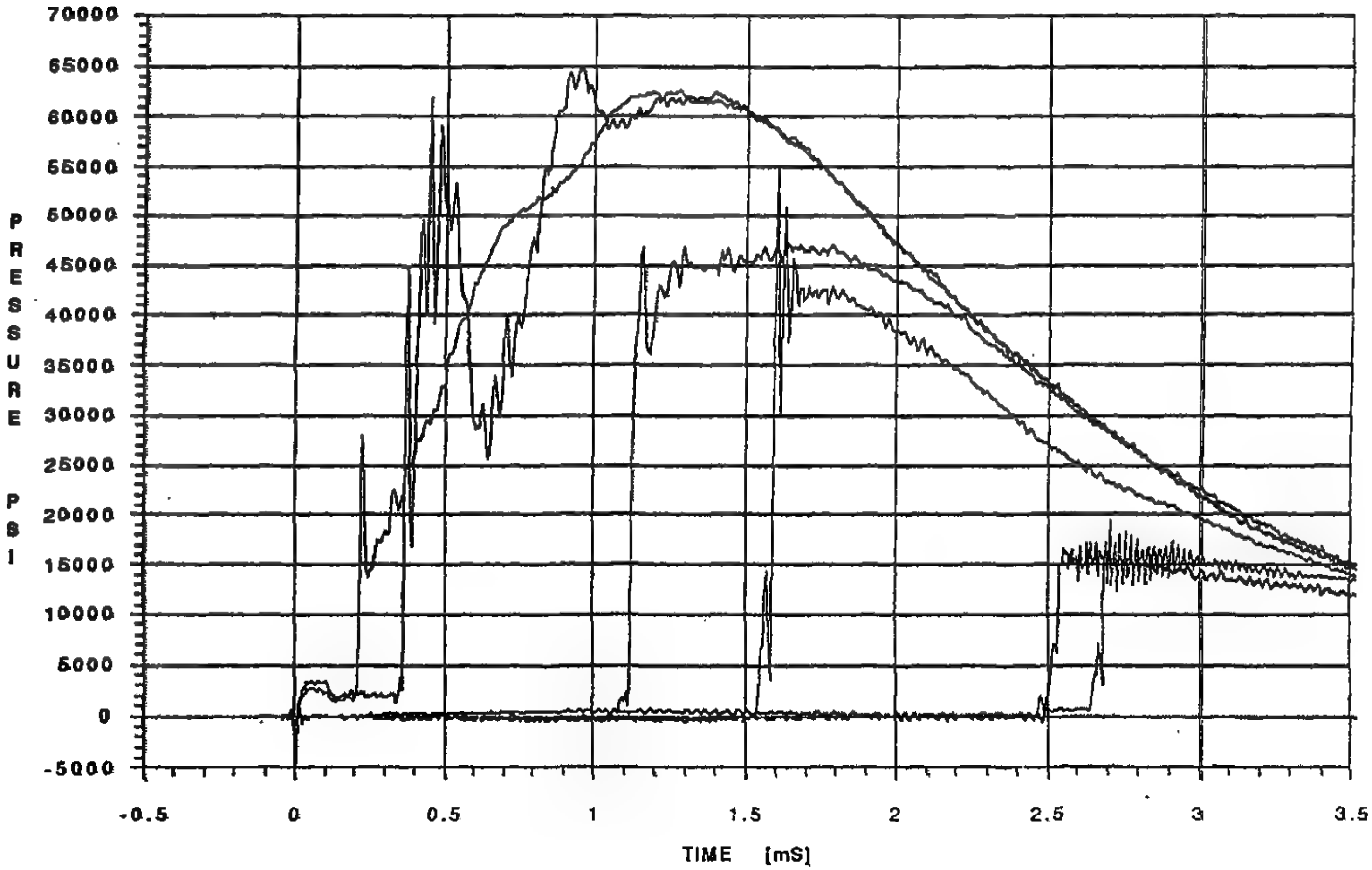
  1) the gas generation rate throughout the chamber, i.e. the "global" rate function,
  2) the spatial distribution of the gas generation rate, and
  3) An Arrhenius equation for the gas phase reaction rate

- The "global" rate function contains two parameters. They describe the distribution centroid and width. These are the most critical parameters and must be chosen by considering electrical input, propellant properties, projectile mass, etc.

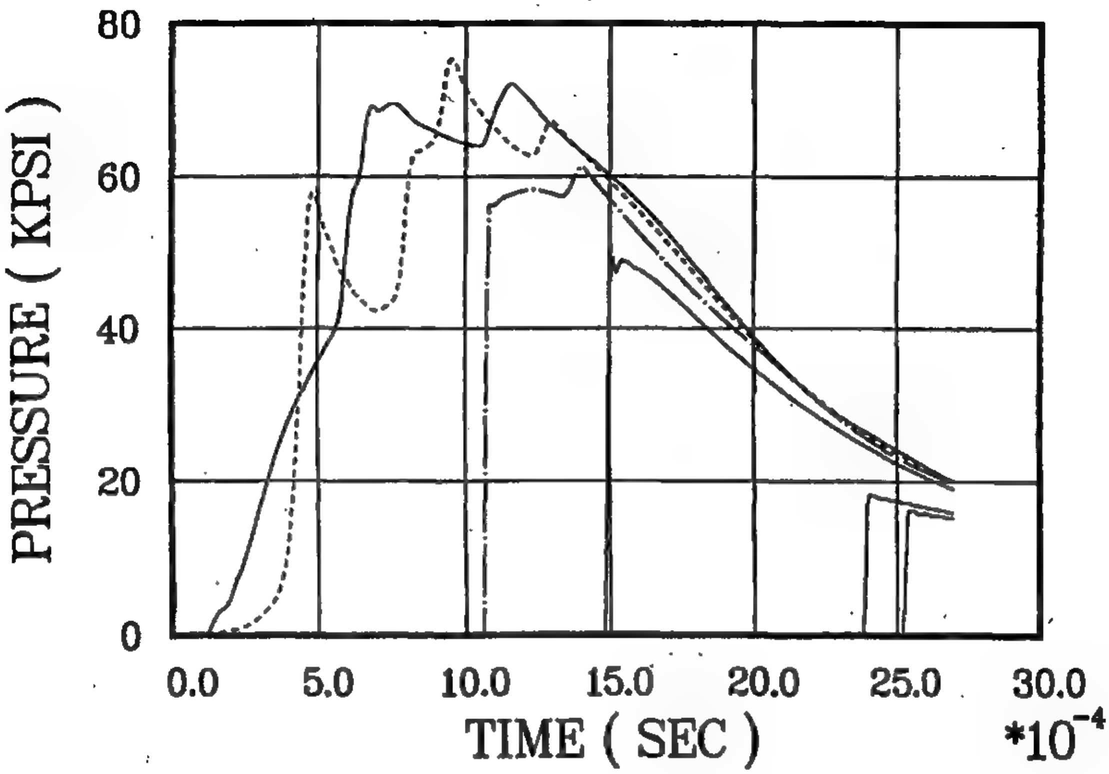
- The spatial distribution function is calculated by considering the normalized product of two densities. The product function of gas and liquid density is likely to be a maximum near the gas-liquid interface. It may be reasonable to assume the spatial maximum of the gas generation rate is near this interface. Two exponential parameters are used to shift the product maximum if desired.

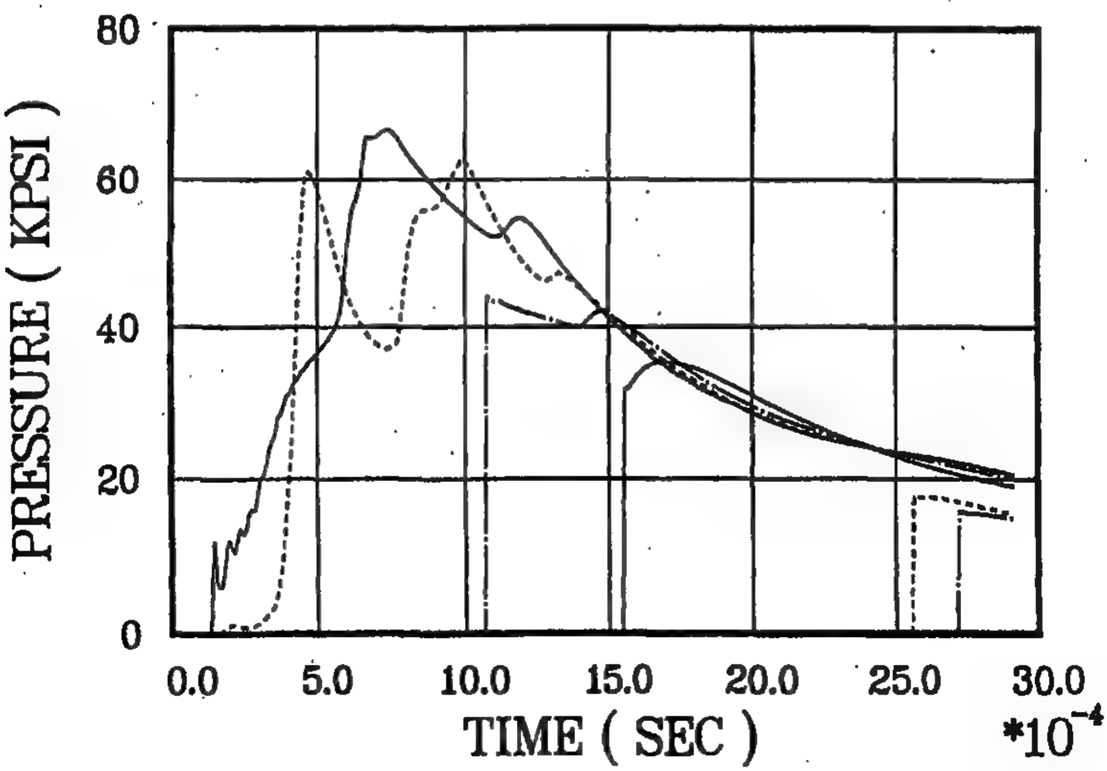
DNA / SAIC ETC PROGRAM

30–mm DNA SHOT 2



30-mm 2-D CALCULATIONS





Thermochemistry

- 2-D 30mm and 1-D 60mm calculations have been performed using peroxide/hydrocarbons as a propellant.
- FMC is currently testing propellants other than peroxide/hydrocarbons with superior properties for weaponization. Tests include propellants consisting of HAN/hydrocarbons. Thermochemical properties have been determined using Blake.
- Thermochemical studies using Blake are being performed to characterize other advanced propellant concepts as well.

FMC

Motivation for 1-D Code Development

- FMC employs workstations at remote testing sites, where real time execution of models is an issue. 1-D calculations often give adequate representation of routine ballistic measurements in a fraction of 2-D execution time.

- Relative simplicity of 1-D codes allows impact of cartridge design details on ballistic performance to be estimated rapidly. A generalized 2-D computational domain requires much greater effort.

- Theoretical sub-models can be tested quickly within a 1-D environment. Generalization from lower to higher dimensionality is often easier than starting from scratch.

Formulation of 1-D Models

- The 1-D models are collections of subroutines that describe the PFN, plasma injector, and the reacting flow. They solve 1-D Euler equations with artificial diffusion.

- A donor cell method is used. A constant number of cells of equal thickness expand to allow for projectile motion.

- The cell volume and face area are design dependent. Cartridge features, such as chamberage, can be introduced by spatial dependence of cell volume and face area. As the grid expands, new areas and volumes are calculated.

- Source terms in the Euler equations are also design dependent.

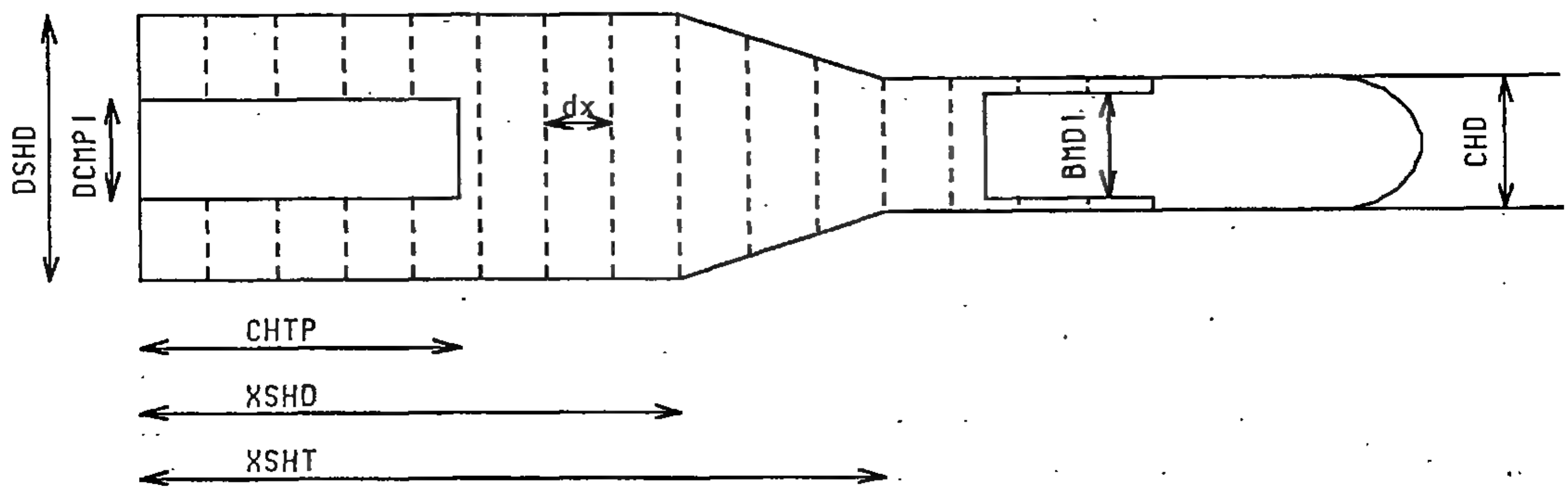
1-D Model Setup - Navy 60-mm Cartridge Design A

The area & volume of each computational cell has been independently calculated to reflect the following design features:

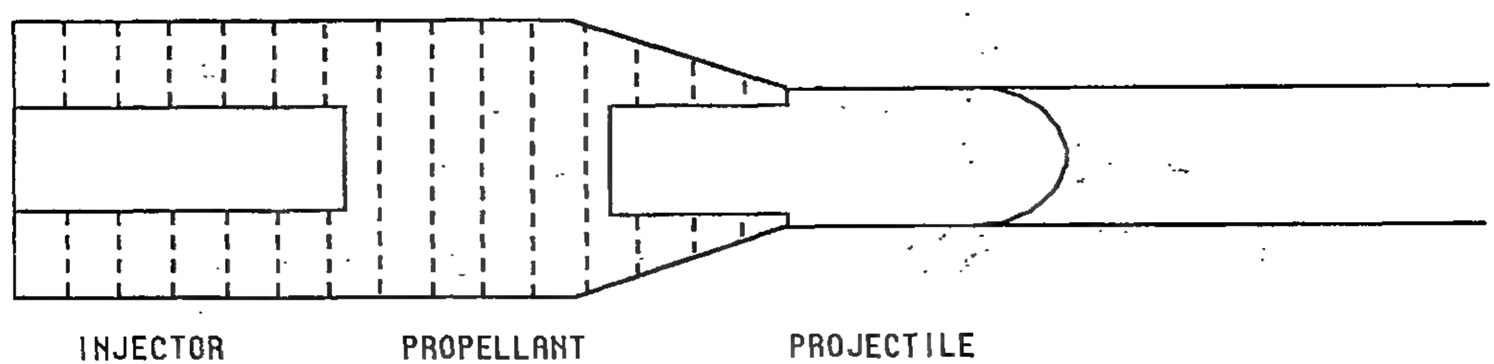
- The injector flow is introduced into the interior of the computational domain; flow is in the reverse direction. The empirical propellant - plasma model has been changed to account for this.

- The domain was changed to describe the shape of the projectile tail. Algorithms for computation of the base pressure and work performed were also changed. Artificial diffusion was added to smooth the abrupt change in area at the projectile tail interface.

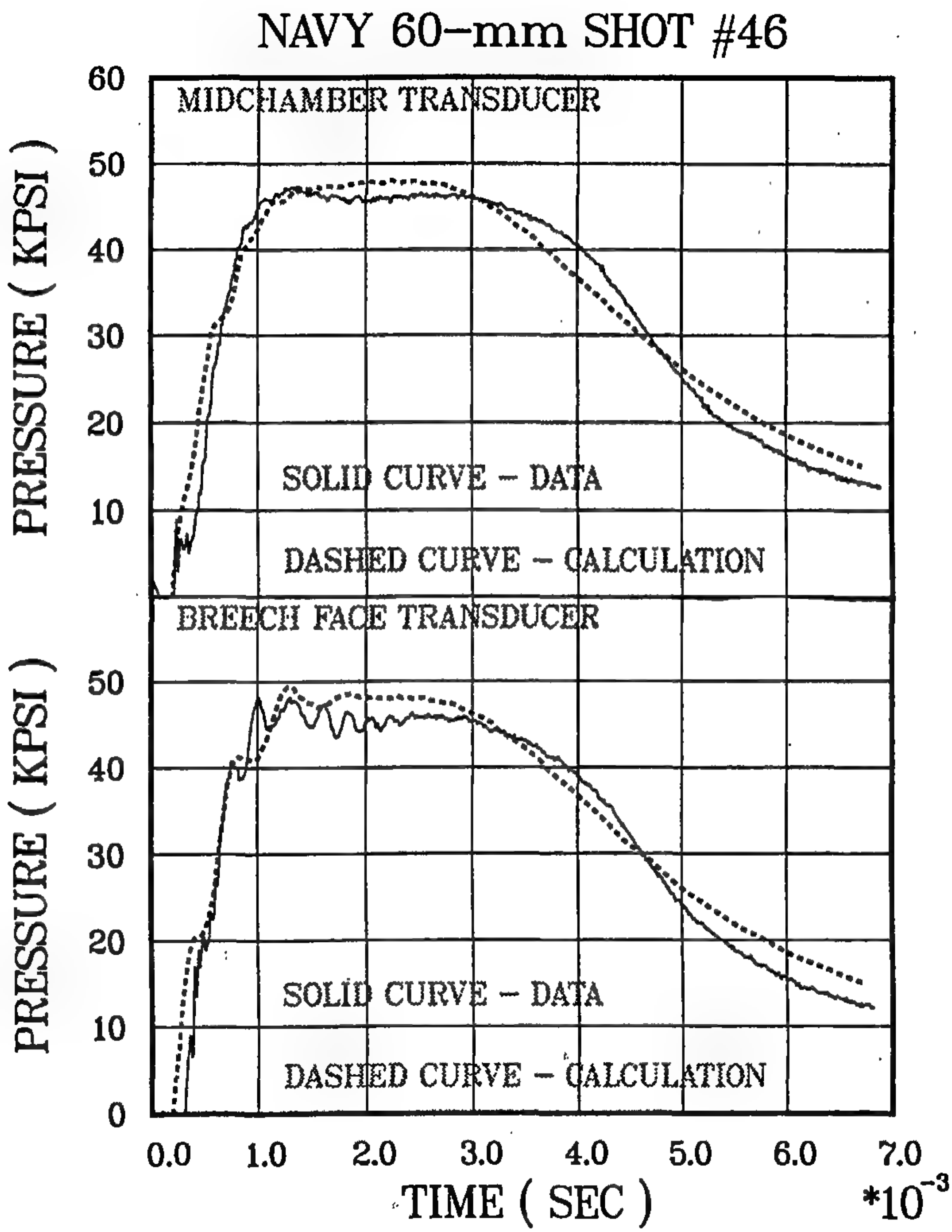
DESIGN A - 1D FLEXIBLE GEOMETRY



INITIAL CONFIGURATION

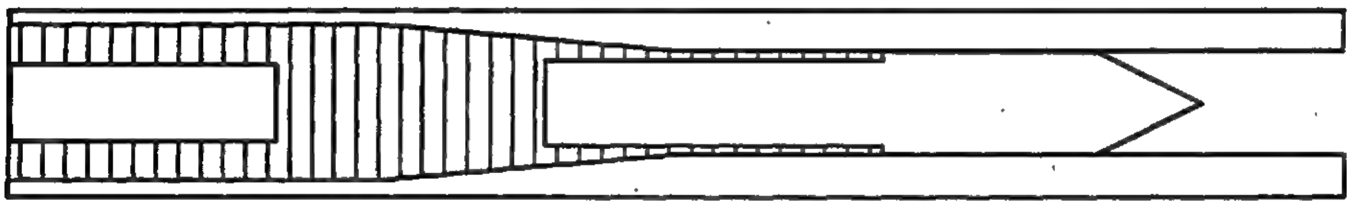


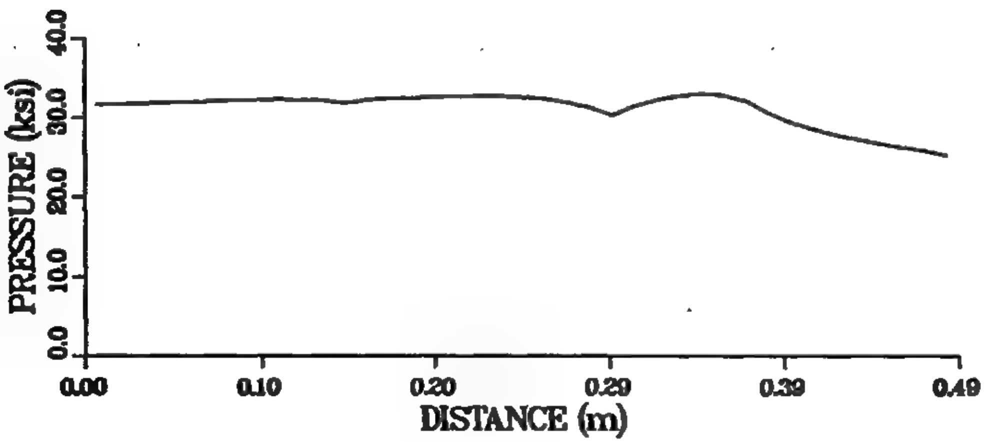
396


NAVY 60-mm SHOT #46
MIDCHAMBER TRANSDUCER
PRESSURE (KPSI)
60
50
40
30
20
10
SOLID CURVE - DATA
DASHED CURVE - CALCULATION
BREECH FACE TRANSDUCER
PRESSURE (KPSI)
50
40
30
20
10
0
SOLID CURVE - DATA
DASHED CURVE - CALCULATION
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
TIME (SEC)
*10^-3

CAP 1–D PRESSURE DISTRIBUTION

TIME = 1.65ms TRAVEL = 11.61cm





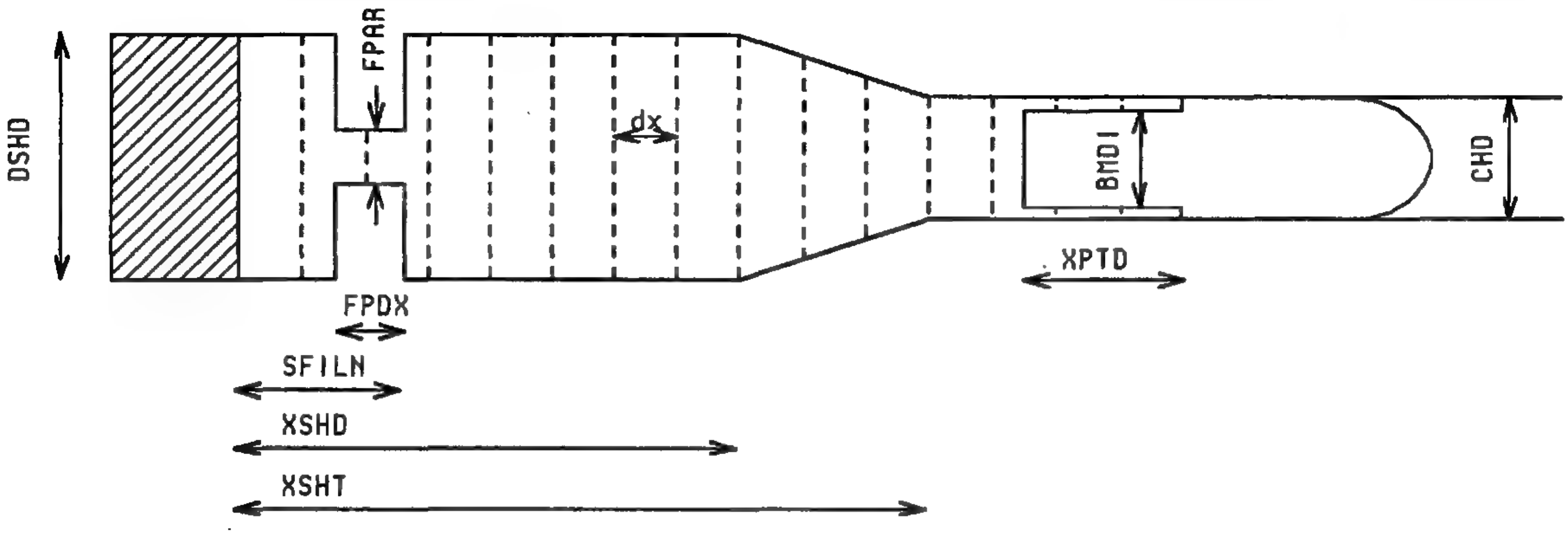
1-D Model Setup - DNA 60-mm SFI Design

The following adaptations have been made to the baseline algorithms:

- **The grid extends only from the area forward of the fuel rich propellant to the rear of the projectile. A regression velocity for the fuel rich propellant surface is calculated so that the injector volume is added to the domain.**

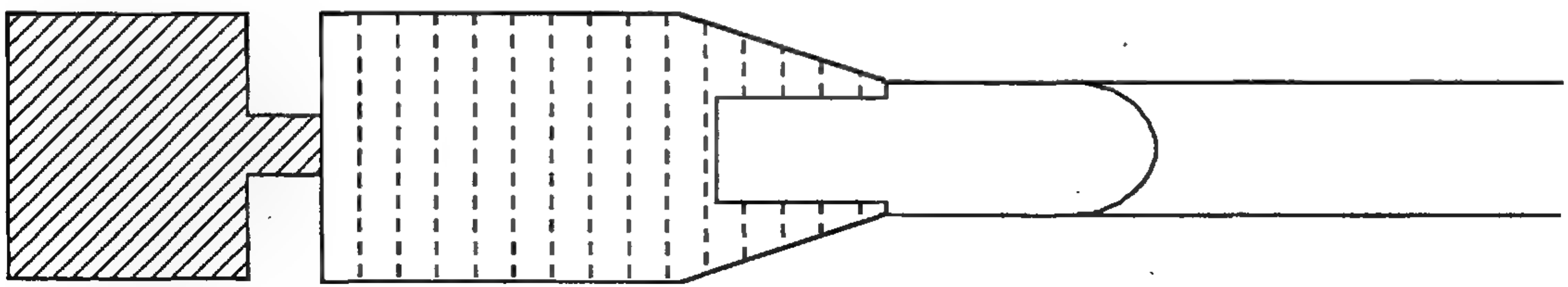
- **The resistance of the injector is modeled by adjusting the geometry of a cylindrical volume to match experimental results. Mass flow from a polyethylene tube. The mass flow is assumed to be largely fluid, not gas.**

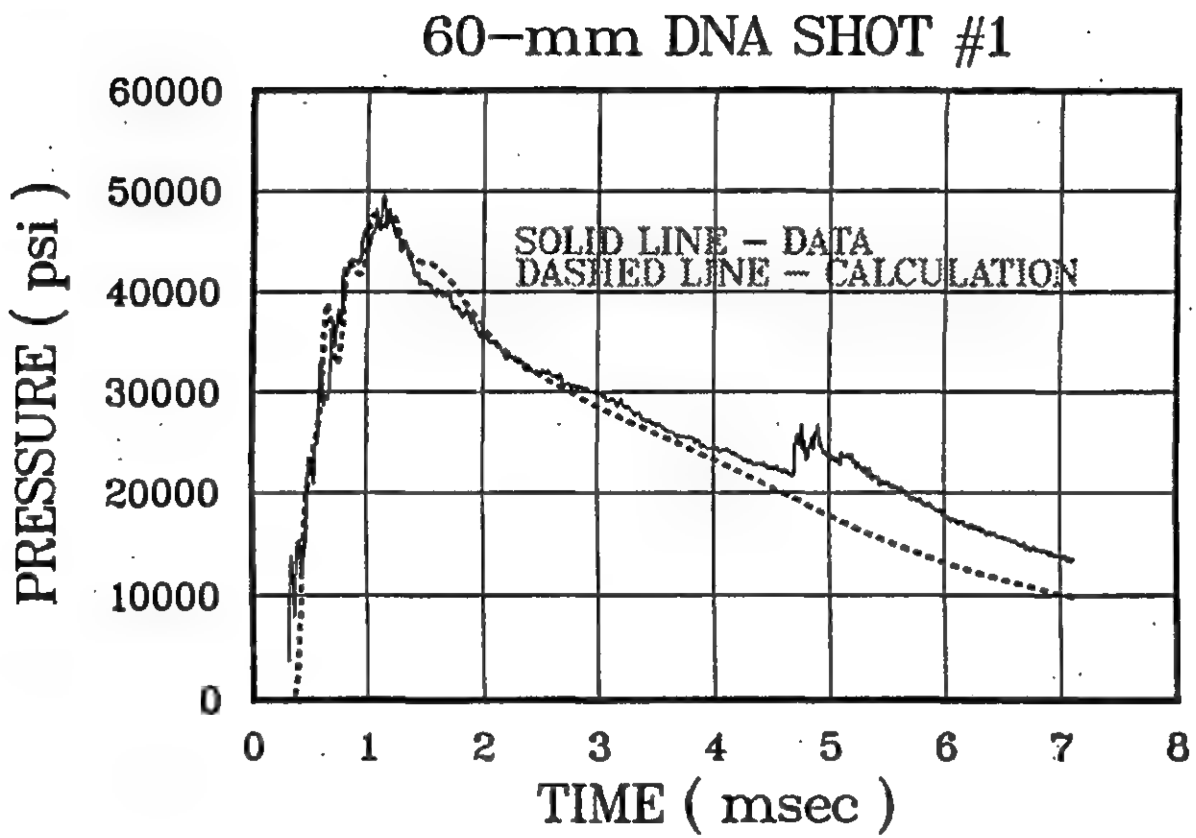
SFI - 1D FLEXIBLE GEOMETRY



116

INITIAL CONFIGURATION



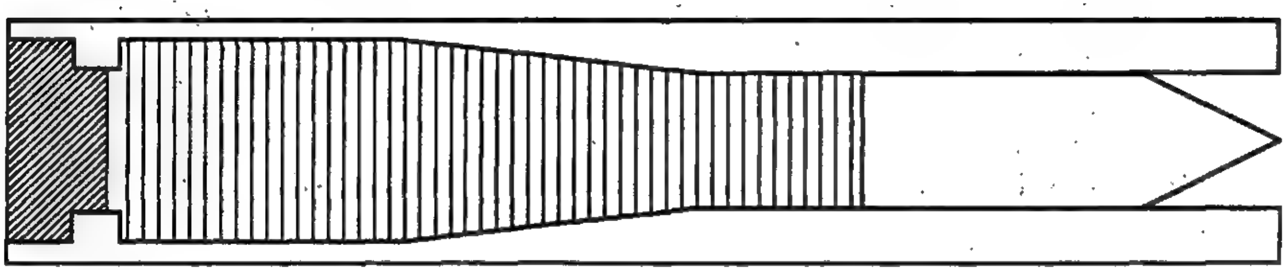


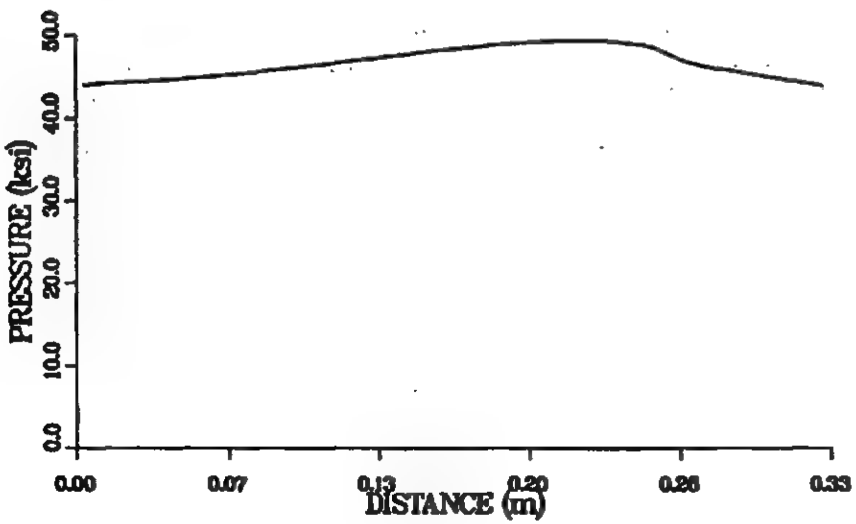
60-mm DNA SHOT #1
SOLID LINE – DATA
DASHED LINE – CALCULATION
PRESSURE (psi)
60000
50000
40000
30000
20000
10000
0
0
1
2
3
4
5
6
7
8
TIME (msec)

117

CAP 1–D PRESSURE DISTRIBUTION

TIME = 1.15 ms TRAVEL = 7.06 cm





118

Impact of 1-D Calculations on 2-D Work

- Effects due to cartridge geometry, i.e. chamberage, projectile tail boom, etc., were found to have significant impact on ballistic calculations. The 2-D computational domain must be generalized to better reflect the hardware.

- The species equations and reaction kinetics model first used in the 60-mm DNA SFI calculations were found to have several beneficial effects. For instance, spatial variation in chamber o/f cannot be included without tracking species equations. Also, the "lag" time that the Arrhenius equation introduces between the chemical energy release rate and gas generation rate inhibited the fuel-oxidizer reaction during electrical pulse onset.

INTENTIONALLY LEFT BLANK.

30-MM ETC BALLISTIC DIAGNOSTIC FACILITY

K. White, I. Stobie, B. Bensinger, S. Driesen,
H. Burden, G. Katulka, and A. Juhasz
US Army Ballistic Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ABSTRACT

The BRL has installed a 30-mm Electrothermal Chemical ballistic diagnostic facility, built under contract by the FMC Corporation. The fixture has the capability of going to pressures as high as 650 MPa with a maximum chamber volume of 550 cc and a projectile travel of 1.53 m (50 caliber). Pressure and temperature measurements can be made in the chamber and down bore. The fixture was built in modular form such that the conventional steel chamber can be replaced by either an optically or x-ray transparent chamber, allowing for flow visualization during the electrothermal process. In addition to the gun mode, the fixture can be operated in either the closed chamber or burst disc mode to examine the effect of a static boundary condition on the ETC process.

The fixture was test fired three times in the gun mode with projectile velocities of over 1000 m/s, peak pressures of 280 MPa and with 60 kJ of electrical energy input. Two tests were performed tin the burst disc mode (65 MPa).

Tests will also be conducted with water as a working fluid and with various plasma-water interface geometries. These tests are to act as a baseline test series of plasma-fluid interactions without chemical contribution from the working fluids. Pressure waves have been observed in ETC firings with reactive fluids and these tests will help to isolate the hydrodynamic processes from the combustion processes. These tests will be carried out with projectiles (moving Boundary layers) and blow-out discs to isolate the effect of the moving boundary layer on the mixing process. In-bore projectile displacement measurements will also be carried out. Tests are in progress and will be discussed.

BALLISTIC RESEARCH LABORATORY

US ARMY
LABORATORY COMMAND

30-MM ETC BALLISTIC DIAGNOSTIC FACILITY

K. White, I. Stobie, B. Bensinger, S. Driesen
H. Burden, G. Katulka and A. Juhasz

JANNAF Workshop
ETC Modeling & Diagnostics
July 9 - 11, 1991

PROGRAM OBJECTIVE

US ARMY
LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

Develop data base of ETC firings for model validation:

- Axial and radial plasma injection configurations,
- Inert and reactive working fluids,
- Moving boundary layer (projectile) & static,
- Short & long electrical pulse,
- Optically/x-ray transparent chamber.

TEST FIXTURE

US ARMY
LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

30-mm fixture

- maximum chamber volume, 550 cc,
- maximum operating pressure, 650 MPa,
- projectile travel, 1.53 m (50 caliber),
- gun or blow-out disc mode,
- measurements,
  - pressure, chamber and barrel,
  - projectile displacement, 35 GHz interferometer, resolution 1mm,
  - optical/x-ray access chamber.

TEST CONDITIONS

US ARMY
LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

Scaling: $(30/120)^3 = 1/64$

	120-mm	30-mm
Electrical energy	4.5 MJ	70 kJ
Chamber volume	9.95 l	155 cc
Projectile mass	11.4 kg	178 g

Problem with scaling for hydrodynamic effects.

Axial and radial plasma injection:

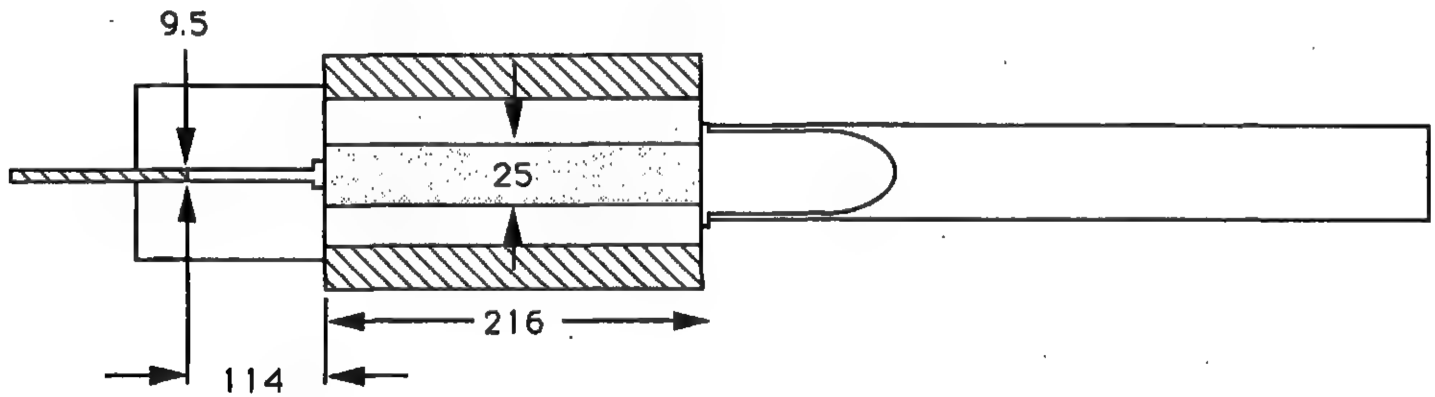
- Inert working fluid, water,
- Moving boundary layer, projectile,
- Short electrical pulse, 300 μs, 70 kJ.

INJECTOR & CHAMBER

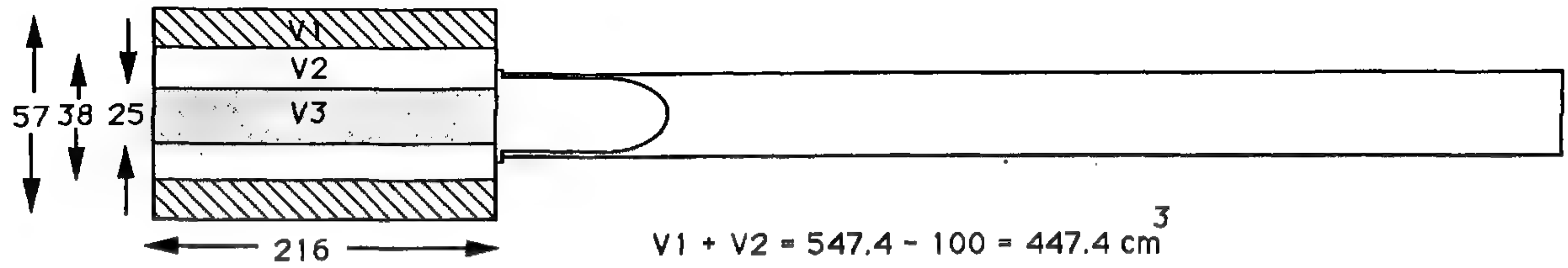
US ARMY
LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

Radial (Center Core)



Radial (Center Core)

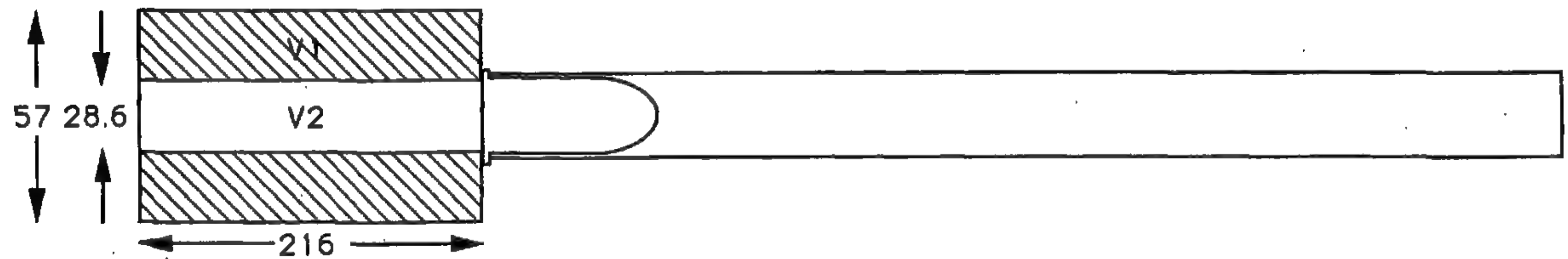


$V1 + V2 = 547.4 - 100 = 447.4 \ cm^3$

$V2 = 247 - 100 = 147 \ cm^3$

$V3 = 100 \ cm^3$ (Styrofoam)

Axial (Center Core)



$V2 = 138 \ cm^3$

M256 (120 mm)

$V = 9950 \ cm^3$

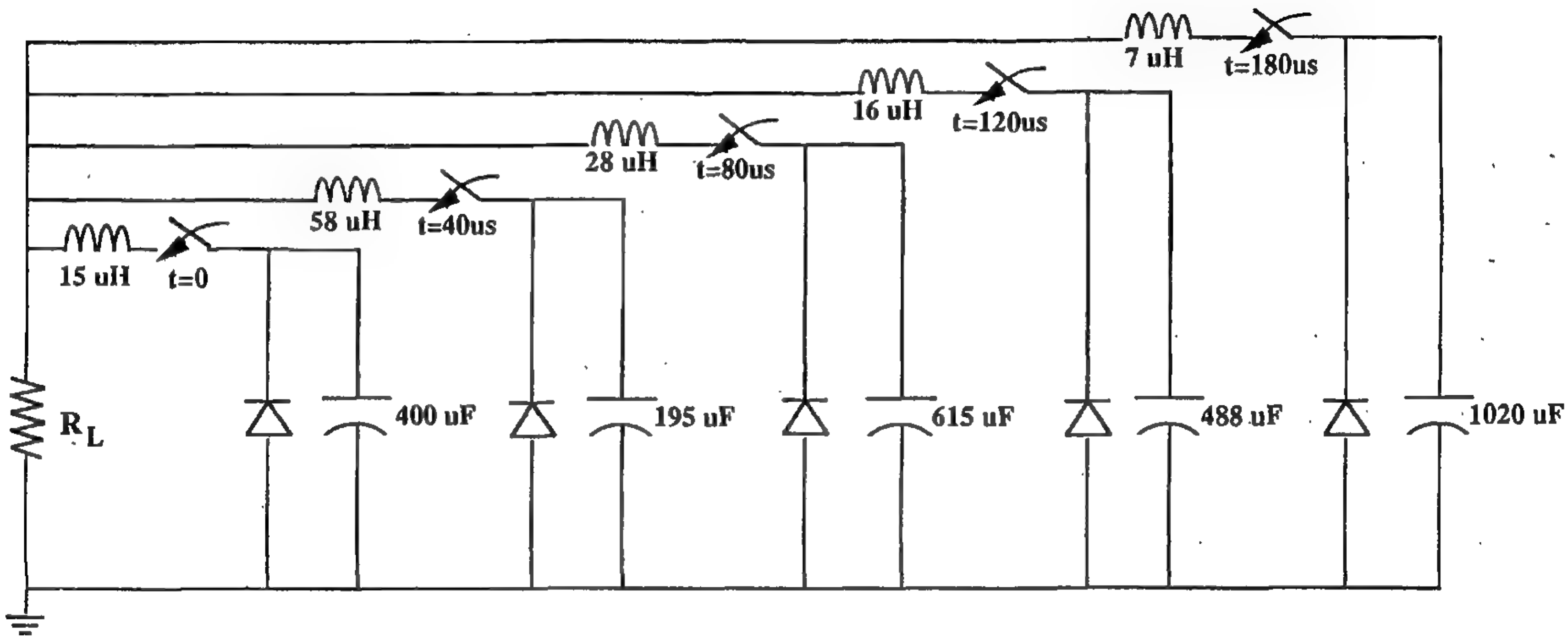
Chamber length = 555 mm

Chamber Diameter = 158 mm

Scaled Value

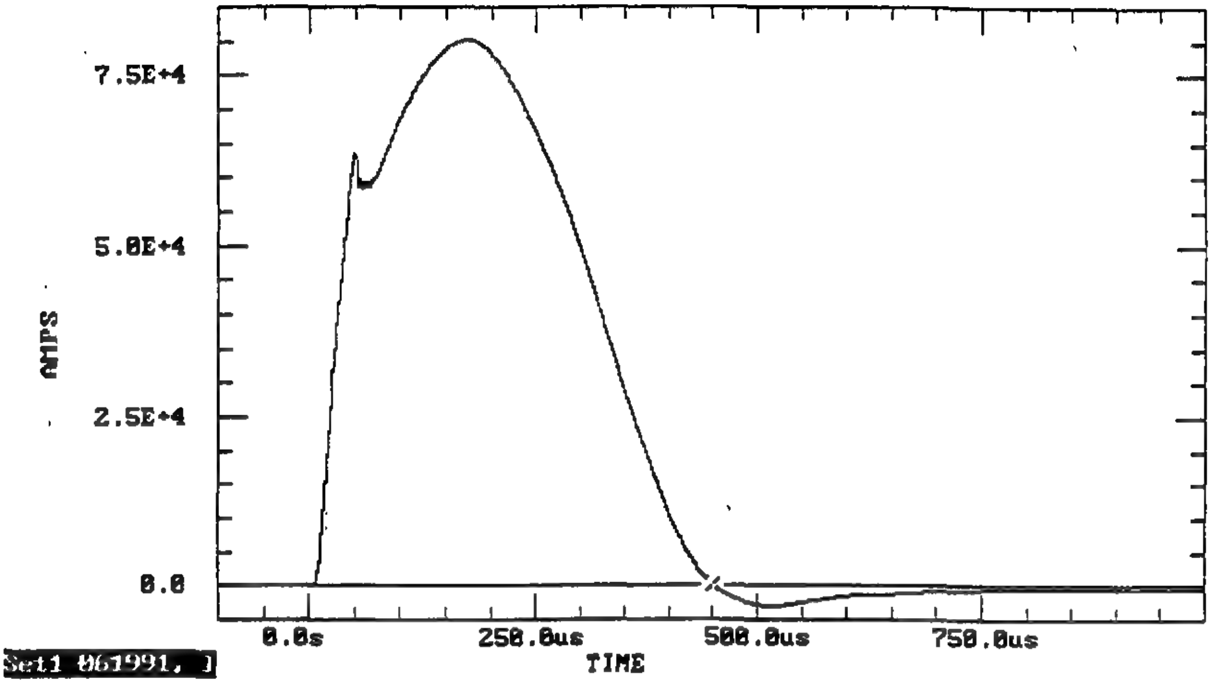
$V = 9950 \ (30 / 120)^3$

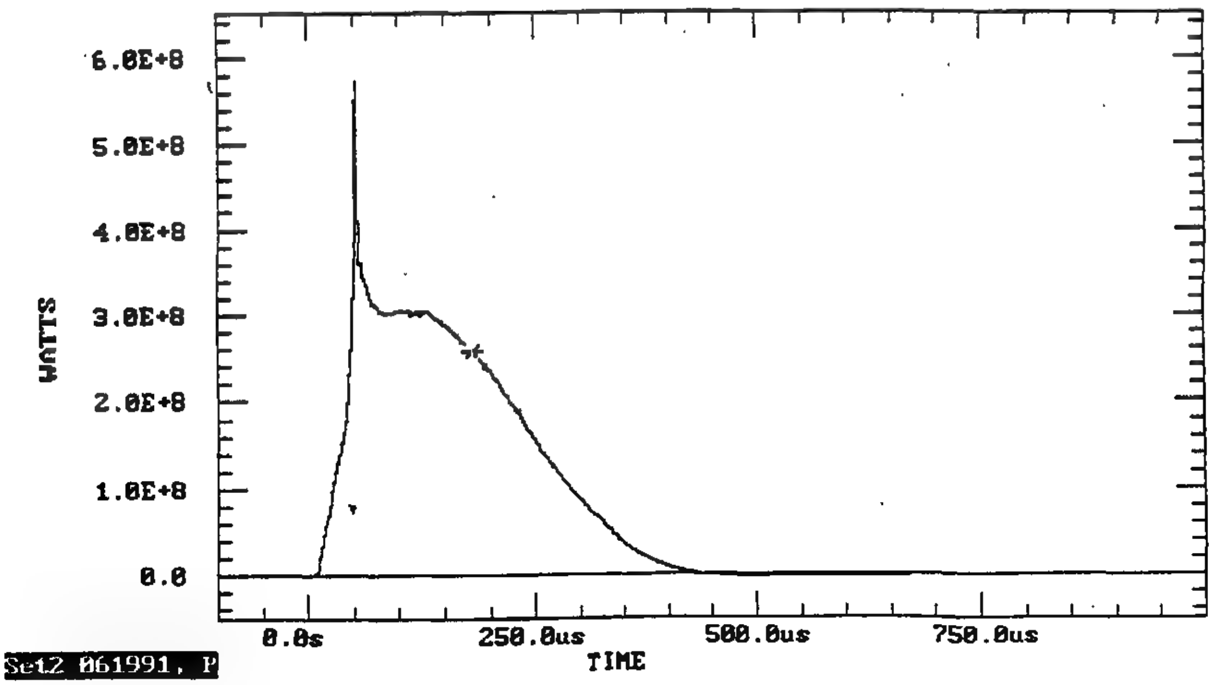
$V = 155 \ cm^3$



Modified BRL five module pulse forming network (135kj at 10kV)

PLASMA INJECTOR CURRENT & POWER

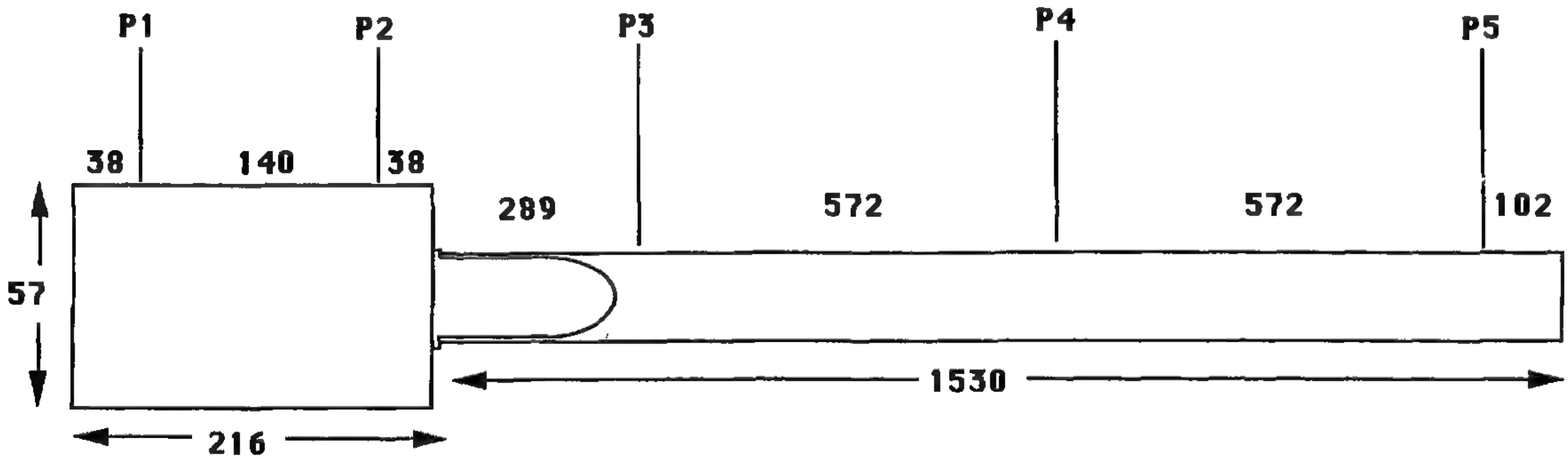




PRESSURE GAGE LOCATION

US ARMY
LABORATORY COMMAND

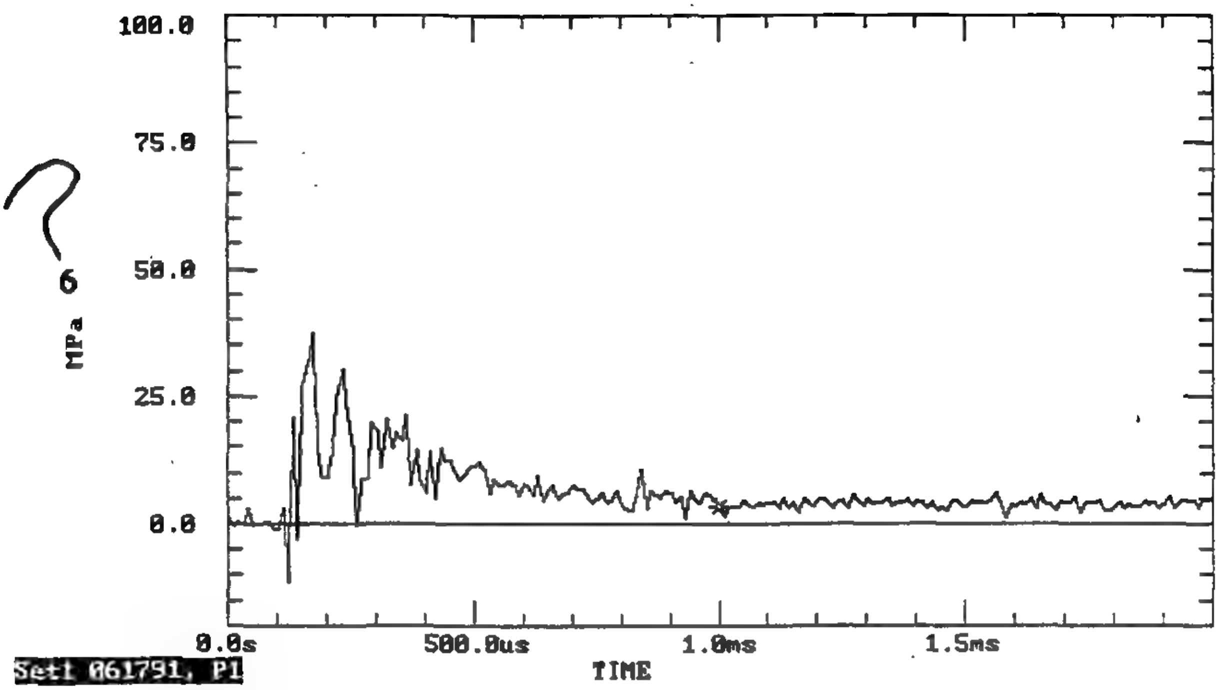
BALLISTIC RESEARCH LABORATORY

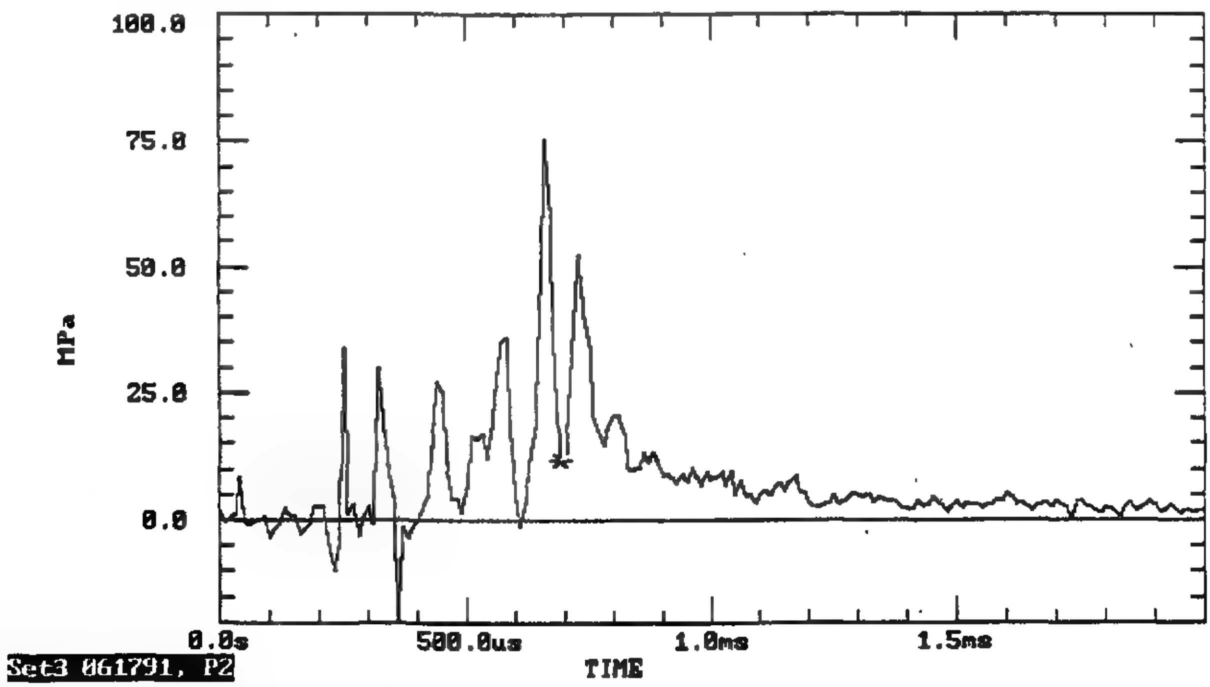


All dimensions in mm .

Chamber Volume = 547.4 cm^3

RADIAL INJECTION WITH LINER





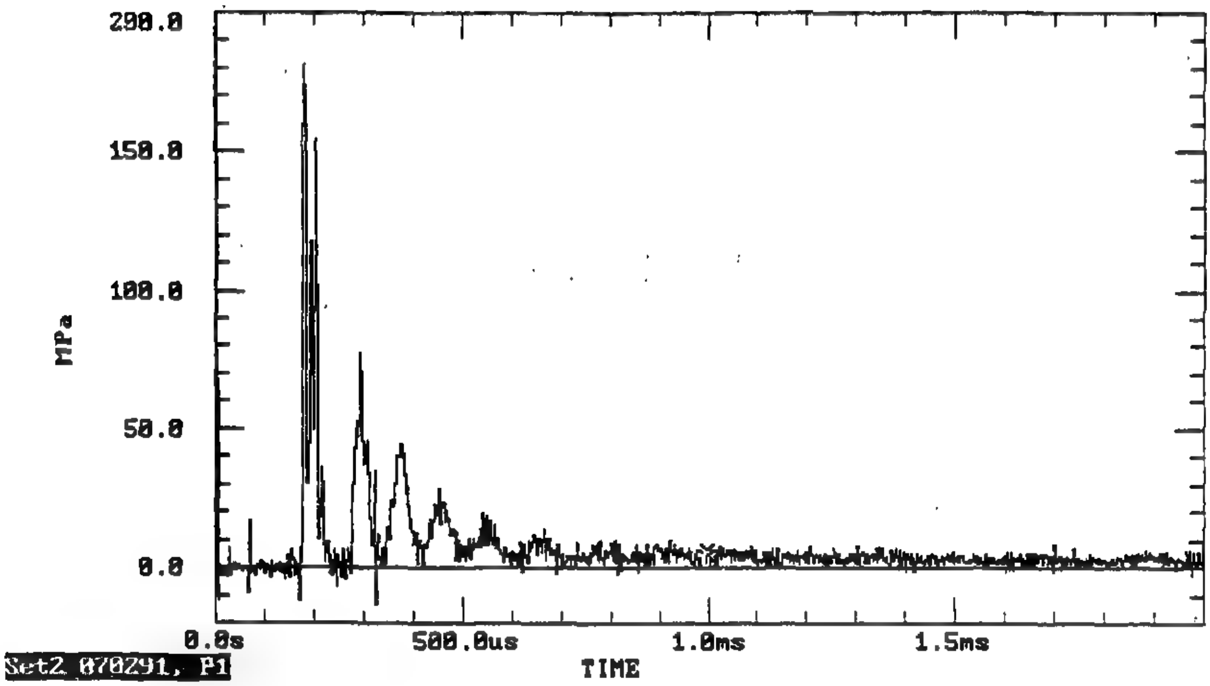
FOURIER ANALYSIS

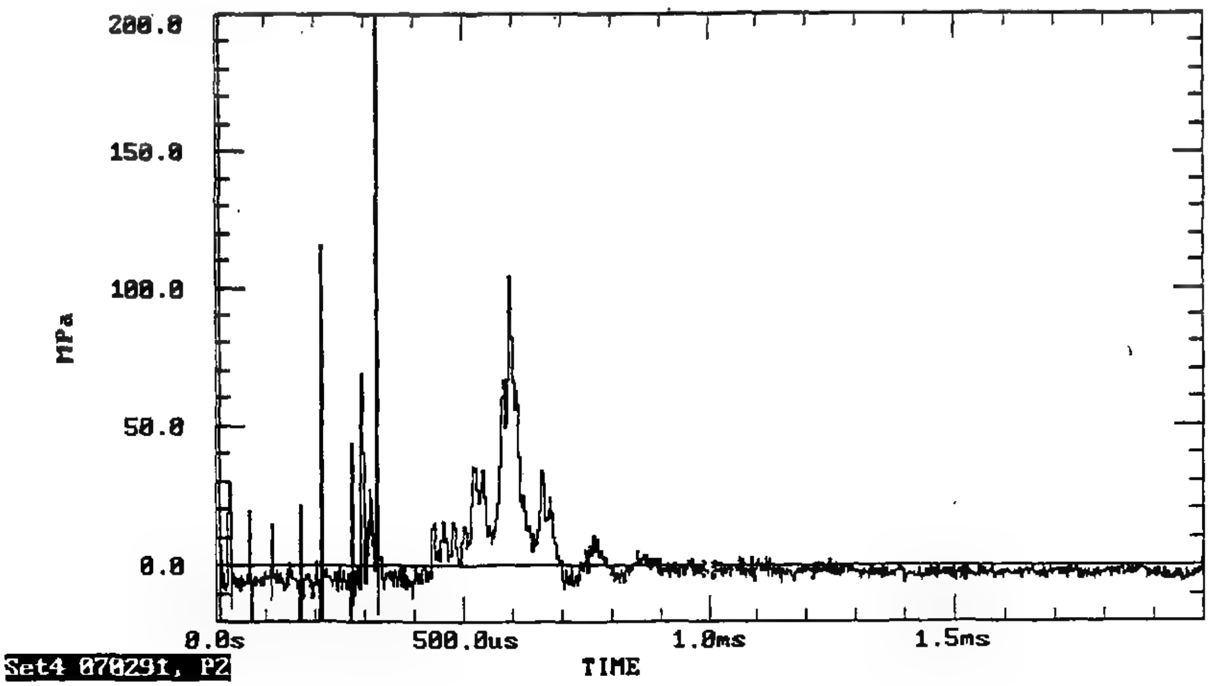
US ARMY
LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

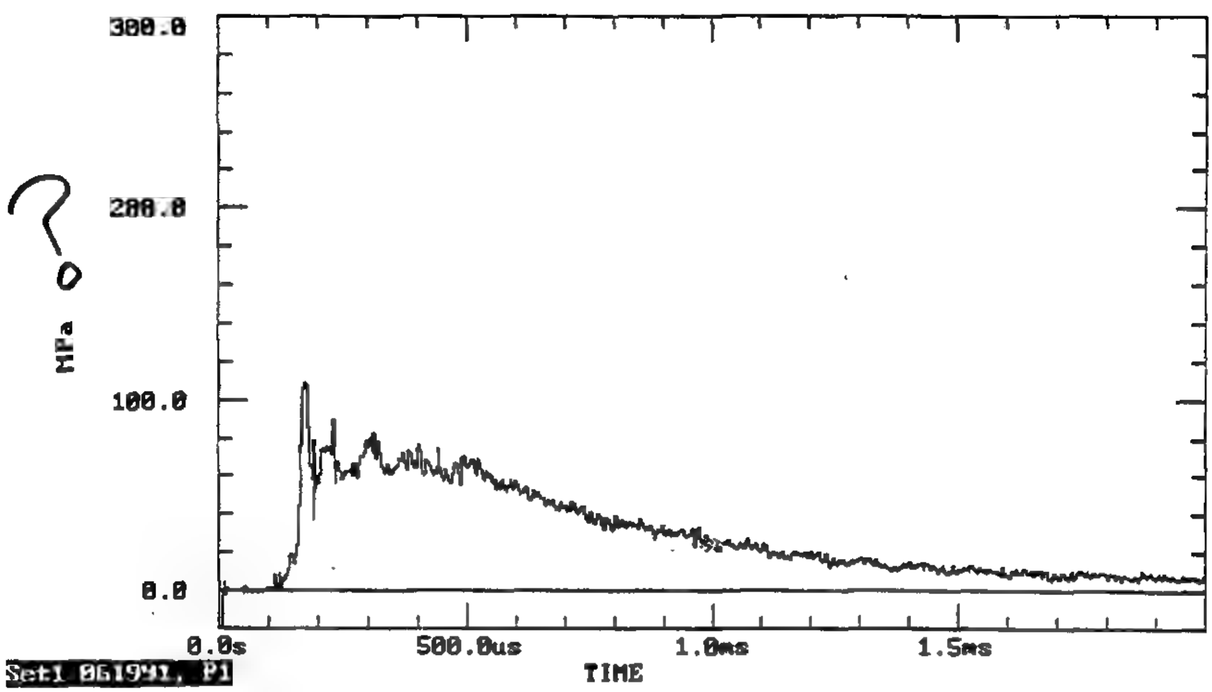
Radial W/O Liner 070291		Axial W Liner 061991		Axial W/O Liner 062091	
P1 kHz	P2 kHz	P1 kHz	P2 kHz	P1 kHz	P2 kHz
10.7	12.6	(2.3)	(2.1)	(3.1)	(2.2)
		5.7	(12.5)	18.4	4.2
		(8.8)		19.5	(15.9)
		14.4		20.9	
				(23.2)	

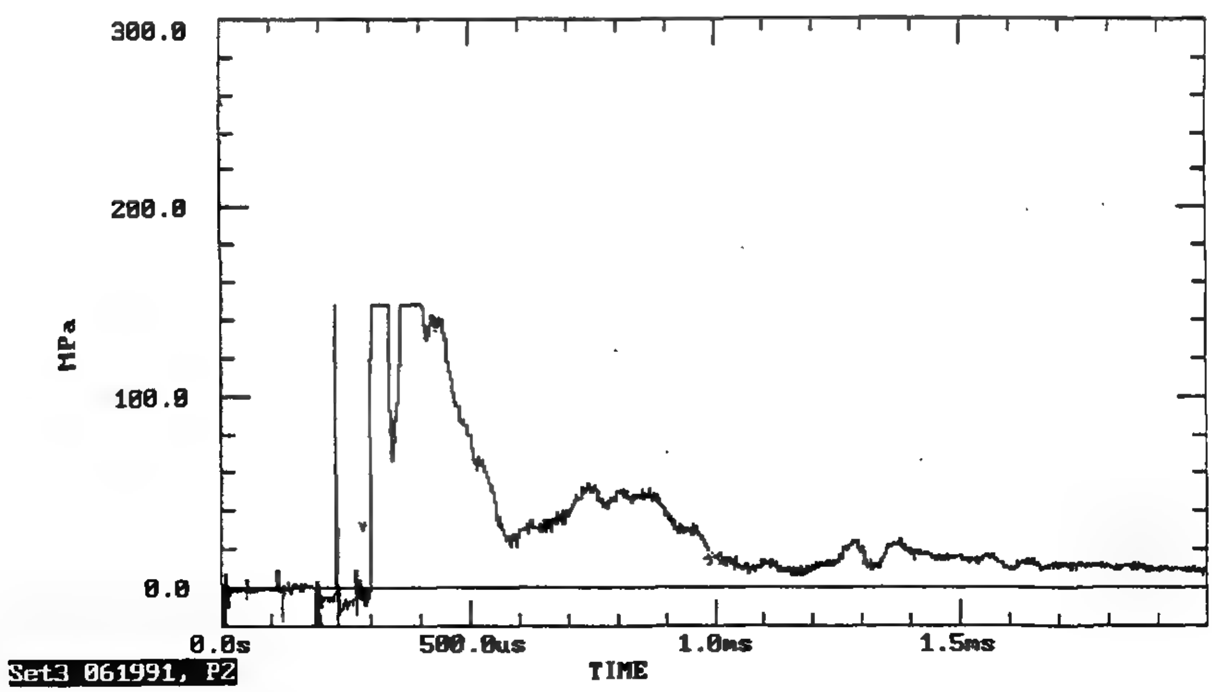
RADIAL INJECTION WITHOUT LINER



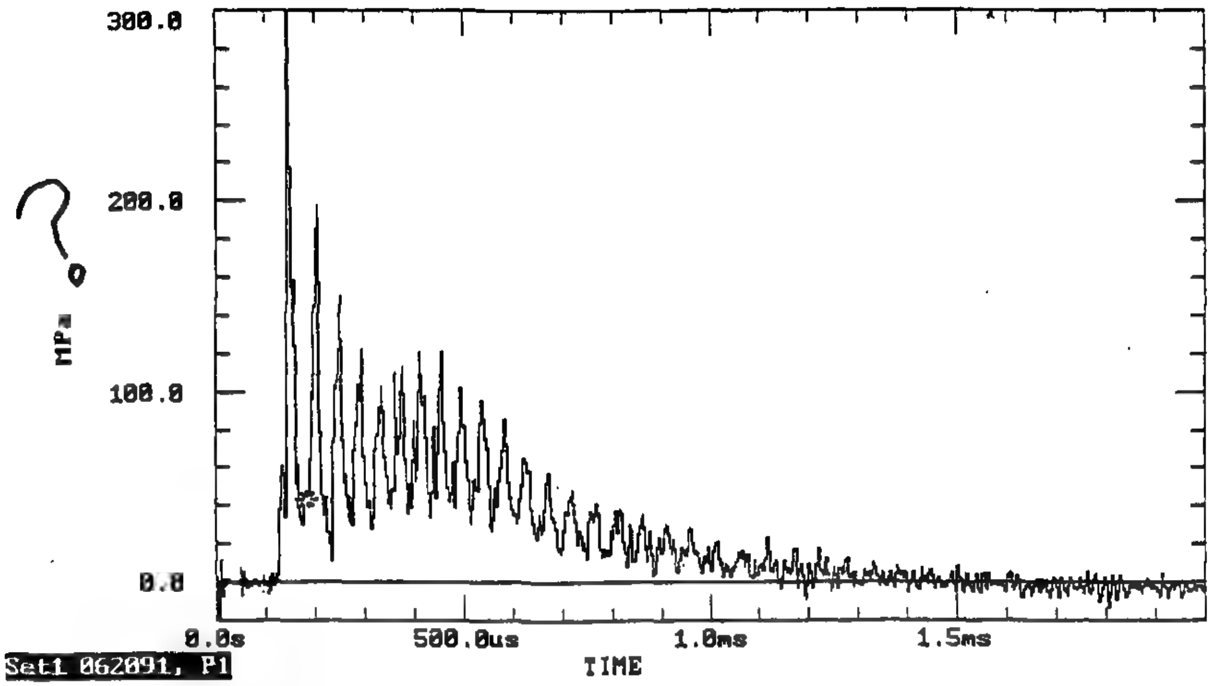


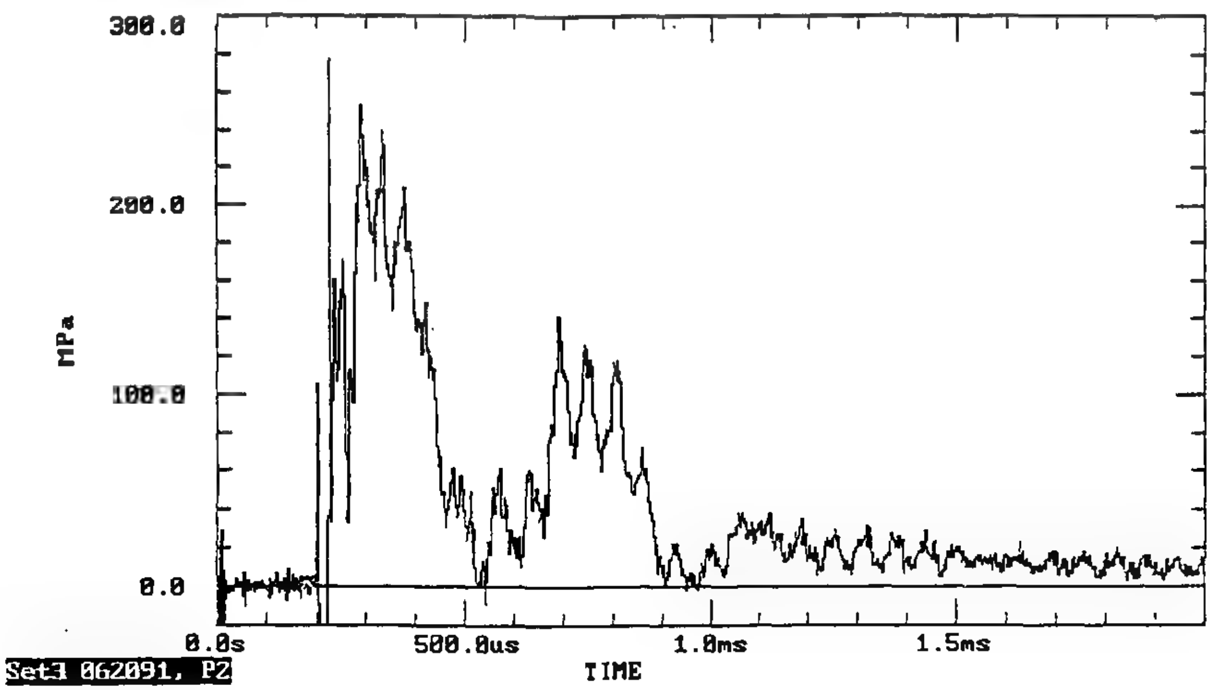
AXIAL INJECTION
WITH LINER





AXIAL INJECTION WITHOUT LINER



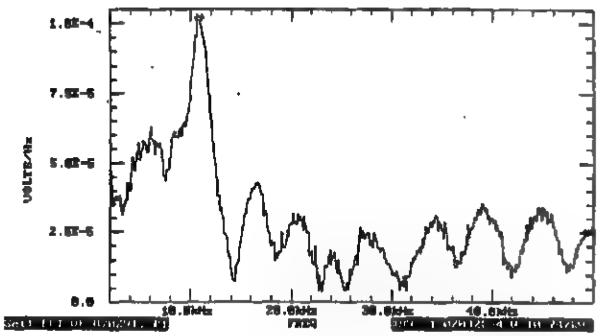


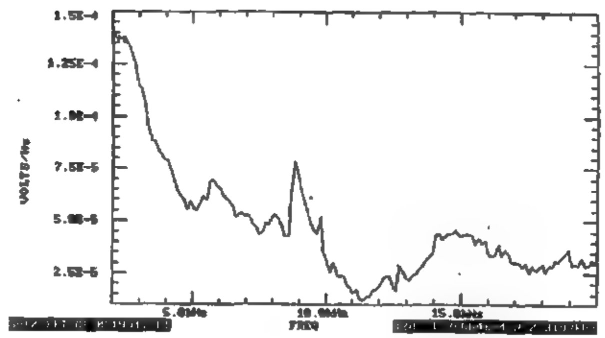
FOURIER ANALYSIS

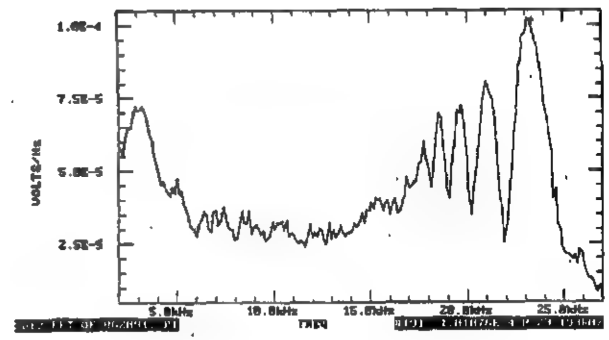
US ARMY
LABORATORY COMMAND

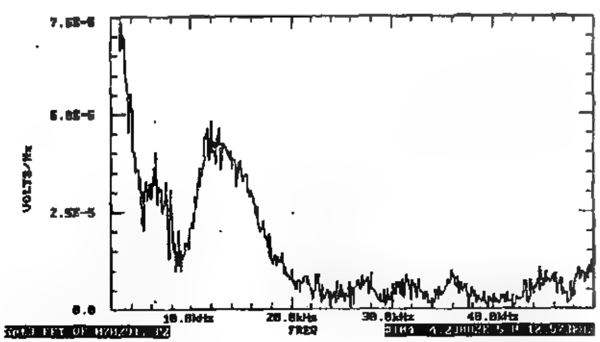
BALLISTIC RESEARCH LABORATORY

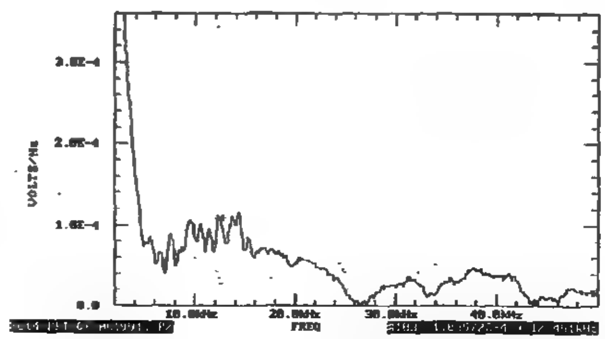
Radial W/O Liner 070291	Axial W Liner 061991	Axial W/O Liner 062091

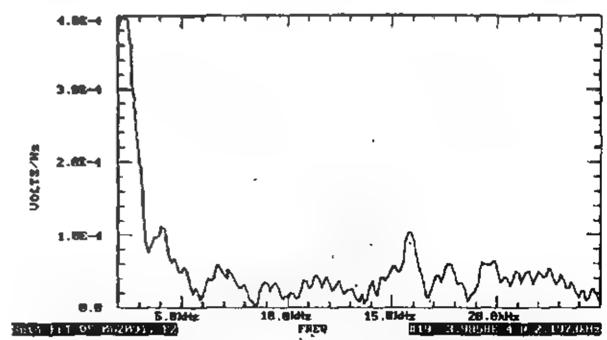












RESULTS

US ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

Radial Injection (Center Core)

ID	P2 MPa	Vol cc	v m/s	liner	ME kJ	EE kJ	Sam. µs	Disp @1ms mm	P MW	Star µs
053091	50	154	73	Y	0.48	-	10	10	-	400
061791	70	131	79	Y	0.56	67	10	12	300	400
062591	>150	423	65	N	0.38	67	2	33.5	300	500
070291	80	383	0	N	0	64	2	-	270	-

Axial Injection

ID	P2 MPa	Vol cc	v m/s	liner	ME kJ	EE kJ	Sam. µs	Disp @1ms mm	P MW	Star µs
061991	>150	136	202	Y	3.63	69	2	85	300	310
062091	200	>500	182	N	2.95	68	2	-	300	-

Note: Water leakage around projectile in test ID 062591.

CONCLUSIONS

US ARMY
LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

Radial (Center Core) vs. Axial Injection

Radial

- more gradual pressure rise at projectile,
- lower pressures and velocities,
- pressure drops off more rapidly.

Issues:

- The water/plasma energy system does not behave as a well stirred system.
- P1 levels suspect,
- Chamber liner may attenuate high frequency waves
  acoustic attenuation,
  longer distance from pressure to gage,
  (10-15 mm).
- Pressures contain substantial high frequency components,
  not combustion driven,

PROPELLANT SURFACE AREA IMPLICATIONS.

FUTURE PLANS

Develop data base of ETC firings for model validation:

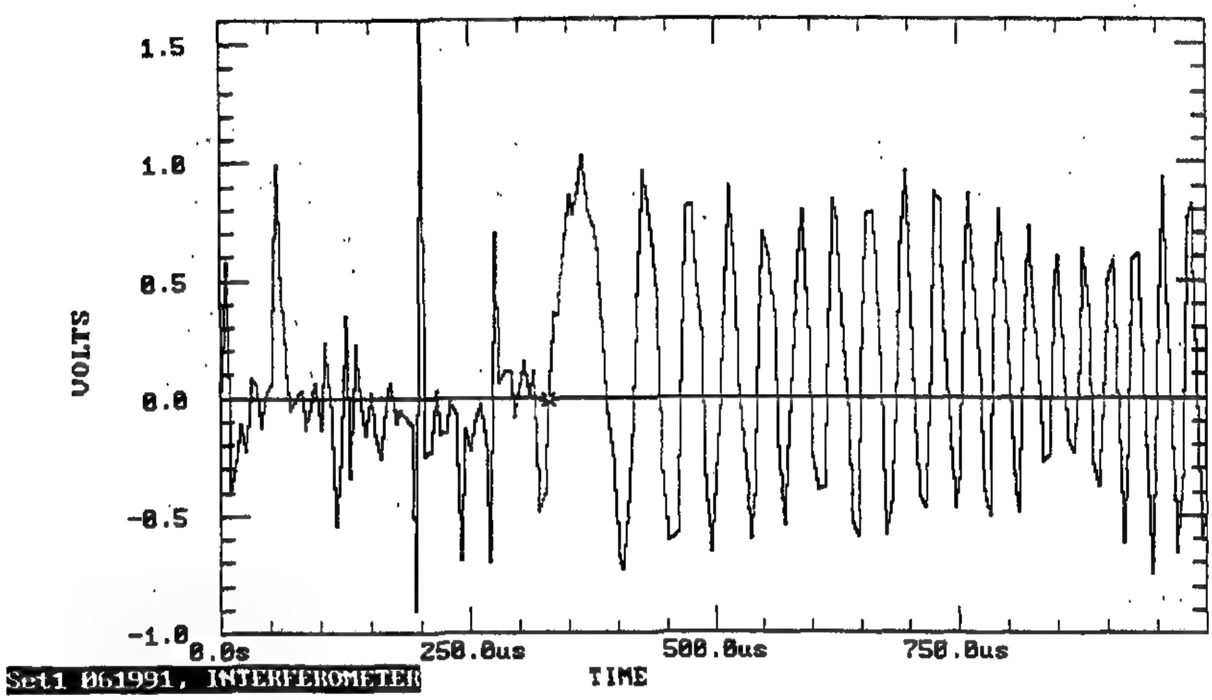
- Axial and radial plasma injection configurations,
- Inert and reactive working fluids,
- Moving boundary layer (projectile) & static,
- Short & long electrical pulse
- Optically/x-ray transparent chamber.

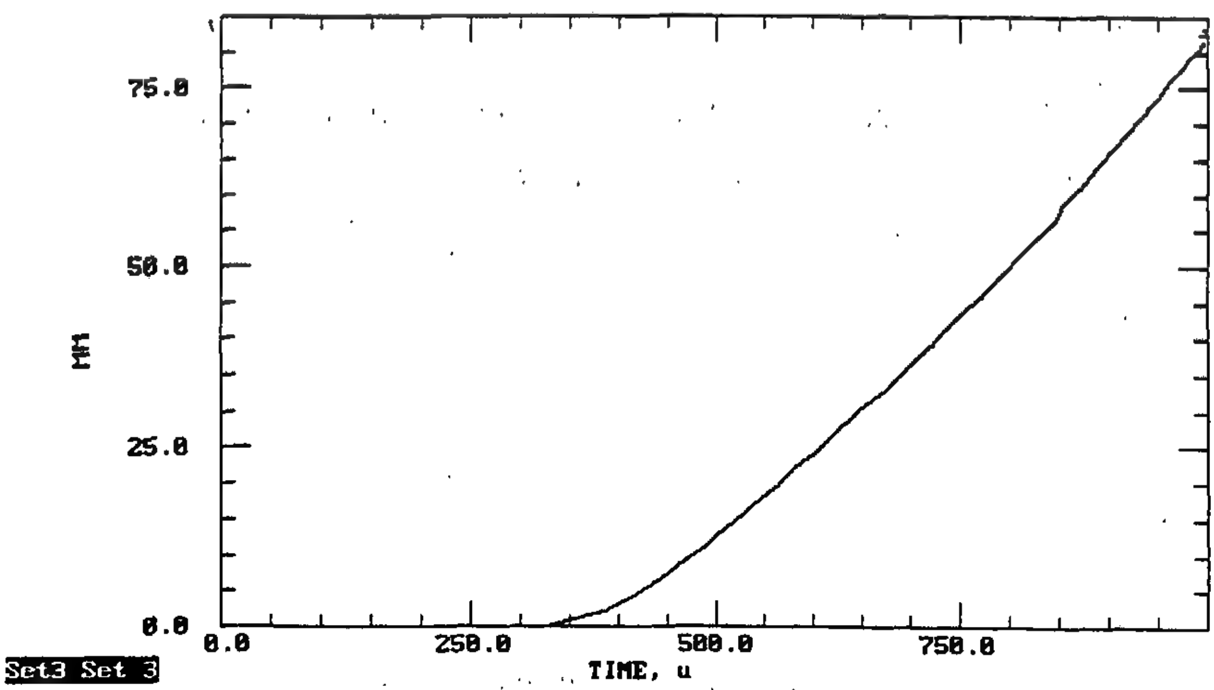
Reactive working fluid:

13-molar HAN,
low energy,
safe & available,
some ballistic data.

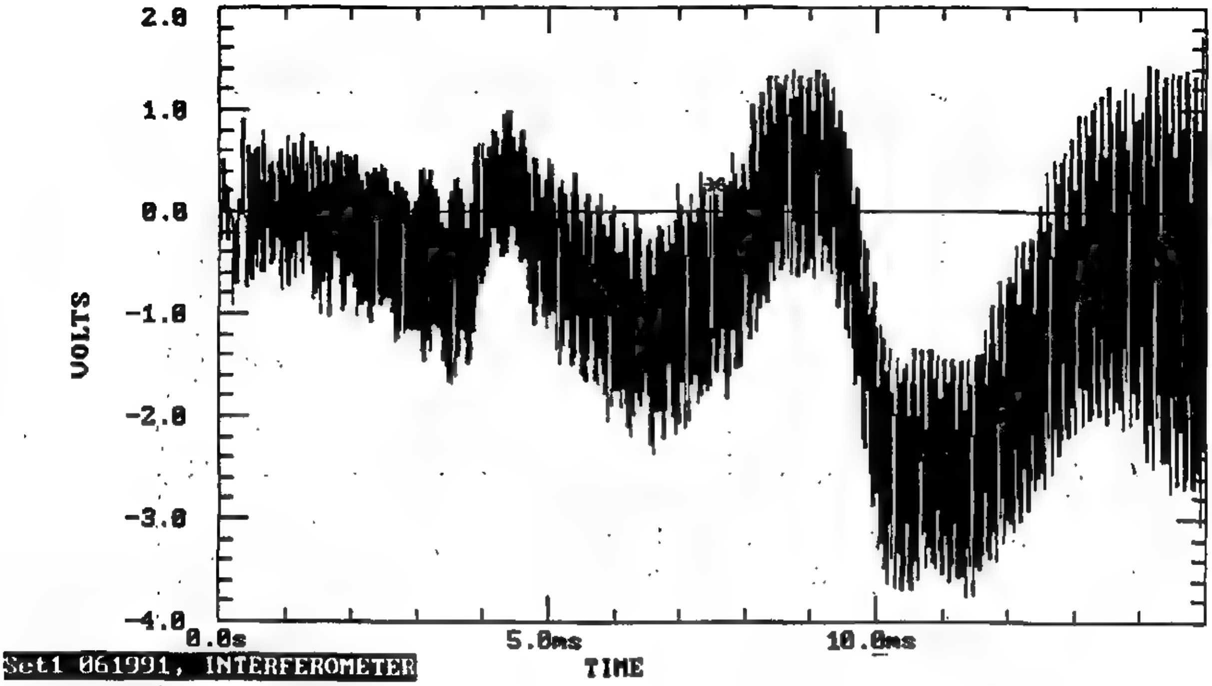
NOS-365, HAN + IPAN +H_2O,
safe & available,
difficult to ignite,
bulk loaded firing data,
mono-propellant.

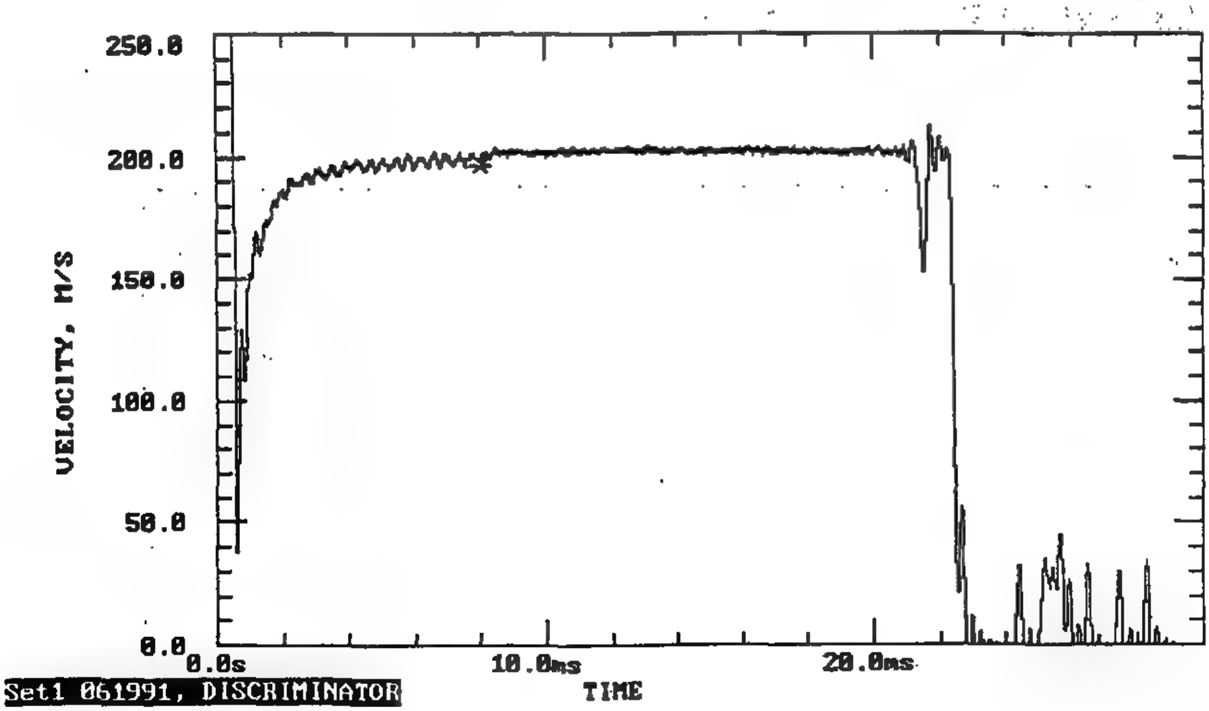
INTERFEROMETER DATA & DISPLACEMENT





INTERFEROMETER & DISCRIMINATOR DATA





INTENTIONALLY LEFT BLANK.

NUMERICAL SIMULATION OF THE INTERIOR BALLISTIC PROCESSES IN AN ETC GUN

J. L. Chen, F. B. Cheung and K. K. Kuo
The Pennsylvania State University
University Park, PA 16802

ABSTRACT

A comprehensive theoretical model has been developed to study the interior ballistic processes in an ETC gun. Phenomena occurring in five separate regions are considered in the model. These regions consist of the gas phase (i.e., Taylor cavity), working fluid (i.e., liquid propellant), dispersed droplets in the Taylor cavity, projectile, and plasma generating cartridge (PGC). Dispersed droplets are generated through the entrainment process as a result of the relative motions between the gas and liquid phases. Governing equations are formulated from the first principles of physics, accounting for the plasma/working fluid interactions and the projectile dynamics. Two different sets of PFN discharge curves have been employed to identify the effects of PFN discharge characteristics on gun performance. Various energy ratios (chemical energy/electrical energy) have been used to investigate how the propulsive energy is influenced by plasma generation and combustion of liquid propellant in different stages of the ETC gun event. The model has been partially validated by comparing the computed breech pressure-time traces with the measured data provided by FMC.

NUMERICAL SIMULATION OF THE INTERIOR BALLISTIC PROCESSES IN AN ETC GUN

J. L. Chen, K. K. Kuo, and F. B. Cheung

Department of Mechanical Engineering

The Pennsylvania State University

University Park, PA 16802

Presented at a JANNAF Workshop on
Electrothermal-Chemical Modeling and Diagnostics

July 9-11, 1991

Ballistic Research Laboratory
Aberdeen Proving Ground, MD

OBJECTIVE

* Develop a Comprehensive Theoretical Model to Investigate the Interior Ballistic Processes of an Electrothermal (ET) Gun

* Predict the Interior Ballistic Processes of an ET Gun

* Seek a Better Understanding of the Mechanisms Controlling the Performance of an ET gun

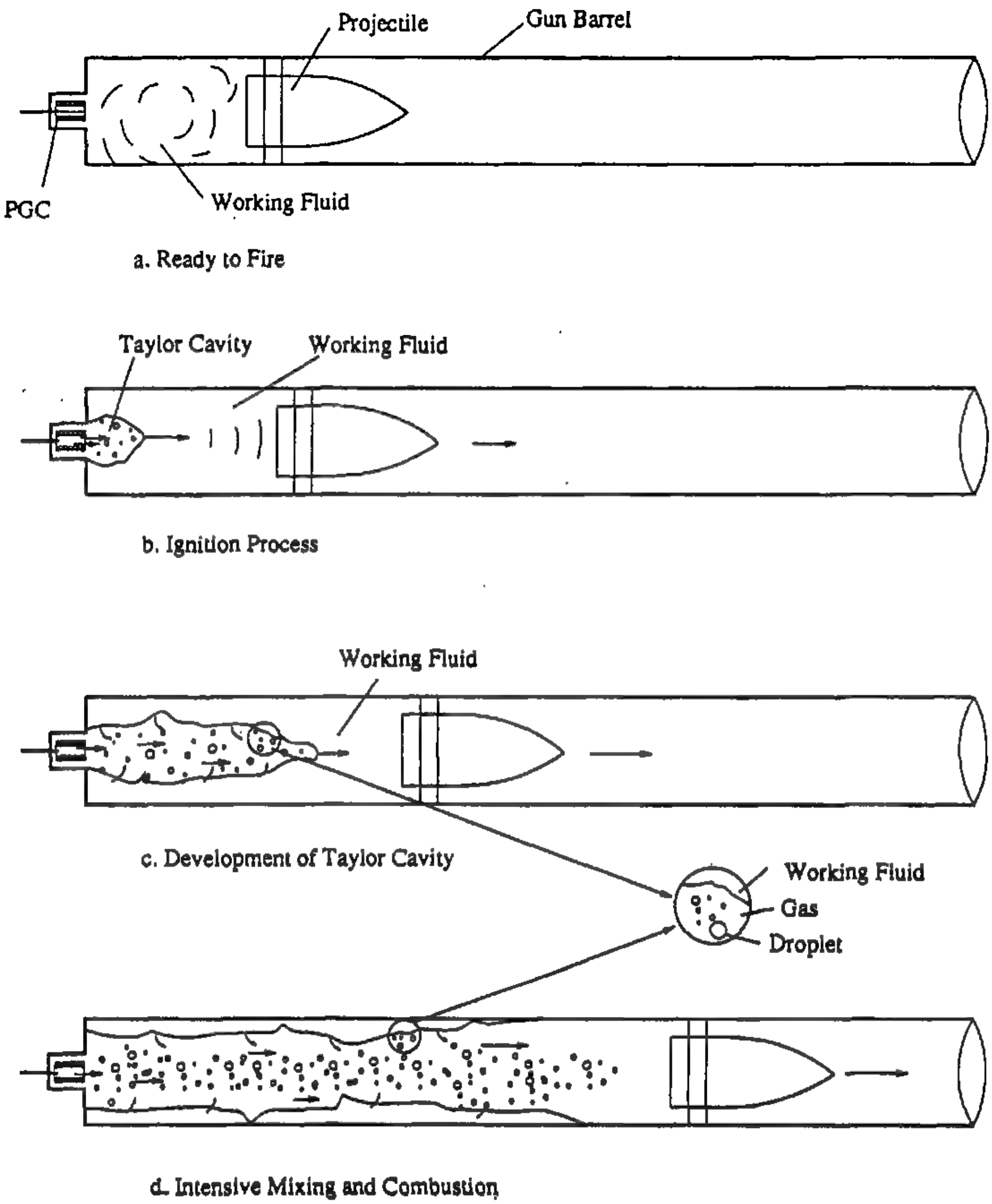
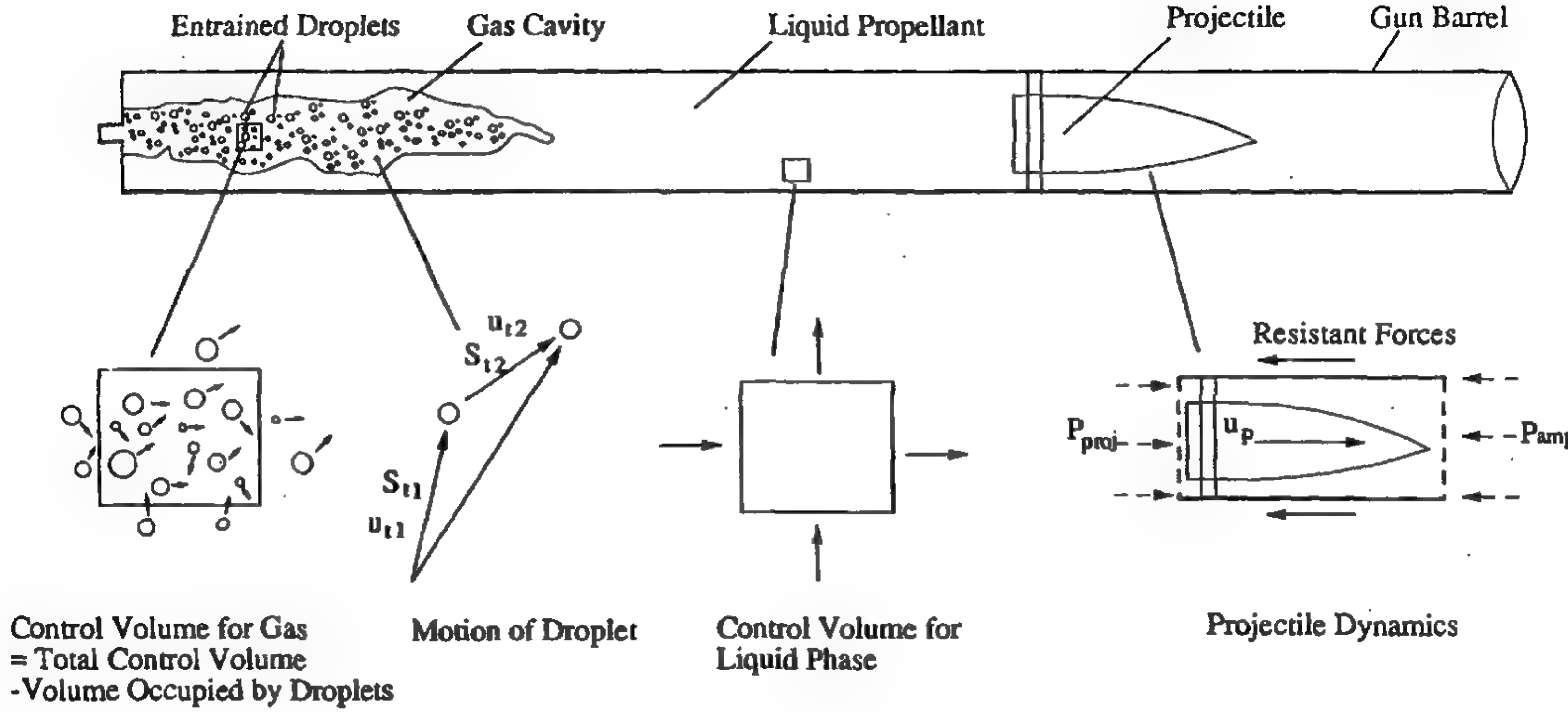


Fig. 1-2 Schematic of a Typical ET Gun Firing Cycle



Control Volumes for Different Phases in an ET Gun

THEORETICAL FORMULATION

Assumptions

1. Gas, Liquid, and Solid Phases:
   Transient Axisymmetric Cylindrical Eulerian Coordinate

2. Motions of the Droplets :
   Small Droplets:
   * Following Gas Flow Motion
   * Number Density Equation

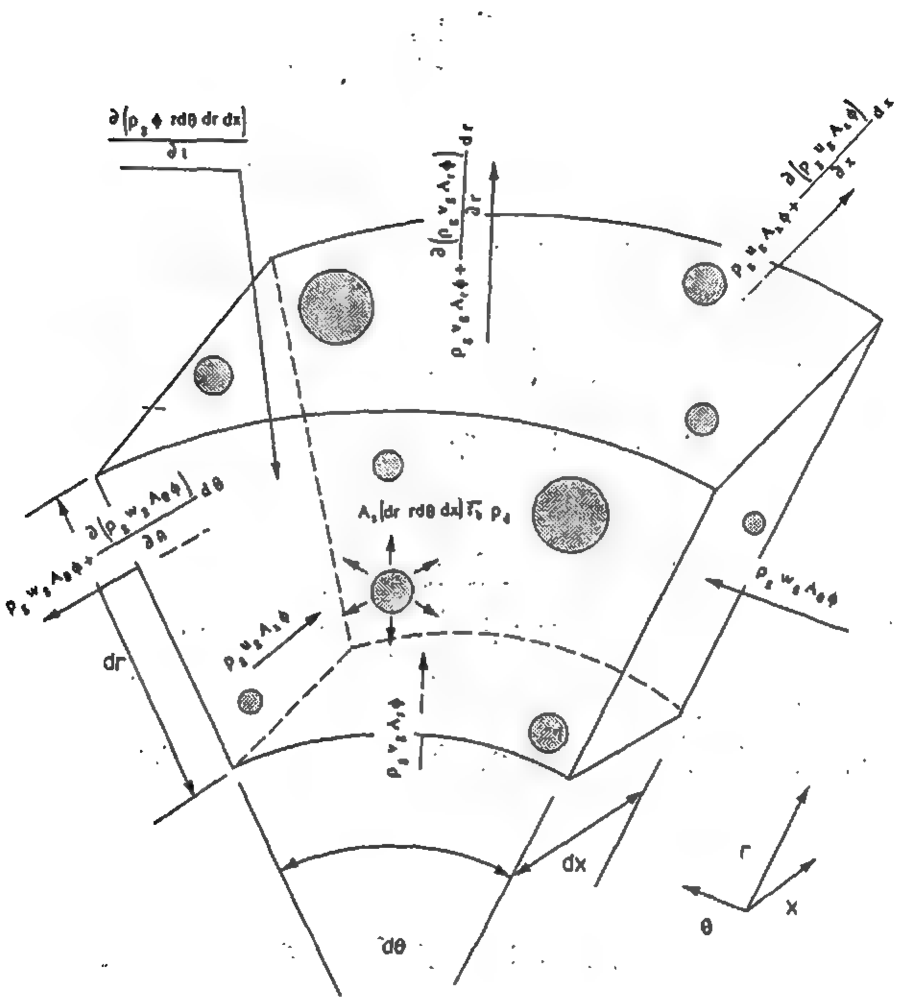
3. Combustion of Liquid Propellant :
   Oxidizer Droplets Burning in the Gaseous Fuel Environment
   (Heat of Vaporization of the Oxidizer is Much Higher than that of the Fuel at Standard State)

4. Combustion Mechanisms of Liquid Propellant :
   Simple Chemical Reacting System (SCRS)
   * Oxidizer, Fuel, and Product
   * One Step Chemical Reaction

5. Body Force Effect : Negligible

Governing Equations for Gas Phase

* Deriving from First Principles of Physics
* Continuity, x-, r-Momentums, and Energy Equations



* Turbulence Closure
  1. Favre Averaged
  2. K, ε Two Equation Model

Gas Phase

Continuity Equation

$$\frac{\partial(\bar{\rho}_g\tilde{\phi})}{\partial t}+\frac{\partial(\bar{\rho}_g\tilde{\phi}\,\tilde{u}_g)}{\partial x}+\frac{\partial(\bar{\rho}_g\tilde{\phi}\,\tilde{v}_g r)}{r\partial r}=\bar{S}_{gm}$$

x-Momentum Equation

$$\frac{\partial(\bar{\rho}_g\tilde{\phi}\,\tilde{u}_g)}{\partial t}+\frac{\partial(\bar{\rho}_g\tilde{\phi}\,\tilde{u}_g\tilde{u}_g)}{\partial x}+\frac{\partial(\bar{\rho}_g\tilde{\phi}\,\tilde{u}_g\tilde{v}_g r)}{r\partial r}$$

$$=-\frac{\partial(\overline{P\phi})}{\partial x}+\frac{\partial}{\partial x}\left[\tilde{\phi}\mu_{eff}\left(\frac{4}{3}\frac{\partial\tilde{u}_g}{\partial x}-\frac{2}{3}\frac{\partial\tilde{v}_g}{\partial r}-\frac{2}{3}\frac{\tilde{v}_g}{r}\right)\right]$$

$$+\frac{\partial}{r\partial r}\left[\tilde{\phi}\mu_{eff}\,r\left(\frac{\partial\tilde{u}_g}{\partial r}+\frac{\partial\tilde{v}_g}{\partial x}\right)\right]-\overline{S_{dx}}+\overline{S_{gx}}$$

r-Momentum Equation

$$\frac{\partial(\bar{\rho}_g\tilde{\phi}\,\tilde{v}_g)}{\partial t}+\frac{\partial(\bar{\rho}_g\tilde{\phi}\,\tilde{v}_g\tilde{u}_g)}{\partial x}+\frac{\partial(\bar{\rho}_g\tilde{\phi}\,\tilde{v}_g\tilde{v}_g r)}{r\partial r}$$

$$=-\frac{\partial(\overline{P\phi})}{\partial r}+\frac{\partial}{\partial x}\left[\tilde{\phi}\,\mu_{eff}\left(\frac{\partial\tilde{u}_g}{\partial r}+\frac{\partial\tilde{v}_g}{\partial x}\right)\right]$$

$$+\frac{\partial}{r\partial r}\left[\tilde{\phi}\,\mu_{eff}\,r\left(\frac{4}{3}\frac{\partial\tilde{v}_g}{\partial r}-\frac{2}{3}\frac{\tilde{v}_g}{r}-\frac{2}{3}\frac{\partial\tilde{u}_g}{\partial x}\right)\right]\frac{\mu_{eff}}{r}\left(\frac{4}{3}\frac{\tilde{v}_g}{r}-\frac{2}{3}\frac{\partial\tilde{v}_g}{\partial r}-\frac{2}{3}\frac{\partial\tilde{u}_g}{\partial x}\right)$$

$$-\overline{S_{dr}}+\overline{S_{gr}}$$

Gas Phase

Energy Equation

$$\frac{\partial(\overline{\rho}_g\tilde{\phi}\,\tilde{H})}{\partial t}+\frac{\partial(\overline{\rho}_g\tilde{\phi}\,\tilde{H}\,\tilde{u}_g)}{\partial x}+\frac{\partial(\overline{\rho}_g\tilde{\phi}\,\tilde{H}\,\tilde{v}_g r)}{r\partial r}$$

$$=\frac{\partial}{\partial x}\left[\tilde{\phi}\,\lambda_{eff}\left(\frac{\partial\tilde{T}_g}{\partial x}\right)\right]+\frac{\partial}{r\partial r}\left[r\,\tilde{\phi}\,\lambda_{eff}\left(\frac{\partial\tilde{T}_g}{\partial r}\right)\right]$$

$$+\overline{\dot{q}}_d-\overline{\dot{q}}_{ht}-\overline{S}_p-\overline{S}_t-\overline{S}_d-\overline{P\frac{\partial\phi}{\partial t}}$$

Equation of State

$$\overline{P}=b\,\overline{\rho}_g\,\tilde{P}+R\,\overline{\rho}_g\,\tilde{T}_g$$

Gas Phase

* Turbulence Model

k Equation

$$\frac{\partial(\overline{\rho}_g k)}{\partial t}+\frac{\partial(\overline{\rho}_g \widetilde{u}_g k)}{\partial x}+\frac{\partial(\overline{\rho}_g \widetilde{v}_g k r)}{r \partial r}$$

$$=\frac{\partial}{\partial x}\left[\left(\frac{\mu_T}{\sigma_k}+\mu_g\right)\frac{\partial k}{\partial x}\right]+\frac{\partial}{r \partial r}\left[r\left(\frac{\mu_T}{\sigma_k}+\mu_g\right)\frac{\partial k}{\partial r}\right]+G_k$$

$$-\frac{\mu_T}{\overline{\rho}_g^{2}}\frac{\partial \overline{\rho}_g}{\partial r}\frac{\partial \overline{P}}{\partial r}-\frac{\mu_T}{\overline{\rho}_g^{2}}\frac{\partial \overline{\rho}_g}{\partial x}\frac{\partial \overline{P}}{\partial x}-\overline{\rho}_g \varepsilon+\overline{A_s \overline{r}_b \rho_d k}$$

ε Equation

$$\frac{\partial(\overline{\rho}_g \varepsilon)}{\partial t}+\frac{\partial(\overline{\rho}_g \widetilde{u}_g \varepsilon)}{\partial x}+\frac{\partial(\overline{\rho}_g \widetilde{v}_g \varepsilon r)}{r \partial r}$$

$$=\frac{\partial}{\partial x}\left[\left(\frac{\mu_T}{\sigma_\varepsilon}+\mu_g\right)\frac{\partial \varepsilon}{\partial x}\right]+\frac{\partial}{r \partial r}\left[r\left(\frac{\mu_T}{\sigma_\varepsilon}+\mu_g\right)\frac{\partial \varepsilon}{\partial r}\right]$$

$$+C_{\varepsilon 1}\frac{\varepsilon}{k}\left(G_k+\frac{\mu_T}{\overline{\rho}_g^{2}}\frac{\partial \overline{\rho}_g}{\partial r}\frac{\partial \overline{P}}{\partial r}-\frac{\mu_T}{\overline{\rho}_g^{2}}\frac{\partial \overline{\rho}_g}{\partial x}\frac{\partial \overline{P}}{\partial x}\right)-C_{\varepsilon 2}\overline{\rho}_g\frac{\varepsilon^2}{k}+\overline{A_s \overline{r}_b \rho_d \varepsilon}$$

with

$$G_k \equiv \frac{4}{3}\mu_T\left[\left(\frac{\partial \widetilde{u}_g}{\partial x}\right)^2-\frac{\partial \widetilde{u}_g}{\partial x}\left(\frac{\partial \widetilde{v}_g}{\partial r}+\frac{\widetilde{v}_g}{r}\right)\right]+\left(\frac{\partial \widetilde{v}_g}{\partial r}+\frac{\widetilde{v}_g}{r}\right)^2$$

$$+\mu_T\left(\frac{\partial \widetilde{u}_g}{\partial r}+\frac{\partial \widetilde{v}_g}{\partial x}\right)^2-\frac{2}{3}\overline{\rho}_g k\left(\frac{\partial \widetilde{u}_g}{\partial x}+\frac{\partial \widetilde{v}_g}{\partial r}+\frac{\widetilde{v}_g}{r}\right)$$

Droplet Phase

Droplet Motion:

Small Droplets Follow Flow Motions

Number Density Equation for Group k

$$\frac{\partial (n_k)}{\partial t} + \frac{\partial (n_k u_g)}{\partial x} + \frac{\partial (n_k v_g r)}{r \partial r} = \underset{(a)}{- C_{1,k} \dot{n}_k} + \underset{(b)}{\sum_{i=k+1} C_{2,i} n_k} + \underset{(c)}{\dot{n}_{k,en}}$$

(a): Due to Combustion of Group k

(b): Due to Combustion of Larger Droplets

(c): Due to Entrainment Mechanisms

Droplet Combustion :

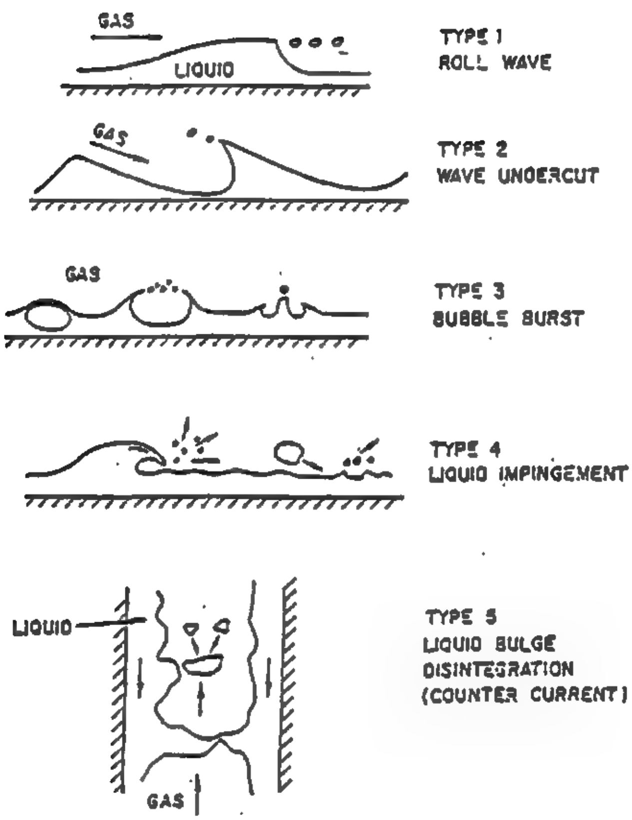
Boundary Condition at Droplet Surface

$P_{i,g} = P_{i,l}$ (at Ambient Pressure)

$f_{i,g} = f_{i,l}$ (at High Pressure), Equality of Fugacity

Entrainment Mechanism

Roll Wave, Wave Undercut, Bubble Burst, Liquid Impingement, Liquid Bulge Disintegration



Droplet Phase

Entrainment Rate:

$$R_A = K_A\left[\frac{W_{LF} - W_{LF,C}}{P_e}\right] u_g^{o2}\ \bar{\rho}_g^{1/2}\ \bar{\rho}_l^{1/2}$$

R_A: entrainment rate

K_A: entrainment coefficient

P_e: wetted perimeter

W_{LF}: liquid film flow rate

$W_{LF,c}$: critical liquid film flow rate

Entrainment Droplet Size

Average Droplet Size Based on a Log Normal Distribution for Annular Flow

$$\frac{d_{32}}{d_t}\left(\frac{\bar{\rho}_g\ u_g^o\ f_s\ d_t}{2\,\sigma}\right)^{1/2} = 2.3 * 10^{-2}$$

d_{32}: Sauter mean diameter

d_t: hydraulic diameter of tube

f_s: friction factor for smooth pipe

σ: surface tension

Projectile Dynamic Motions

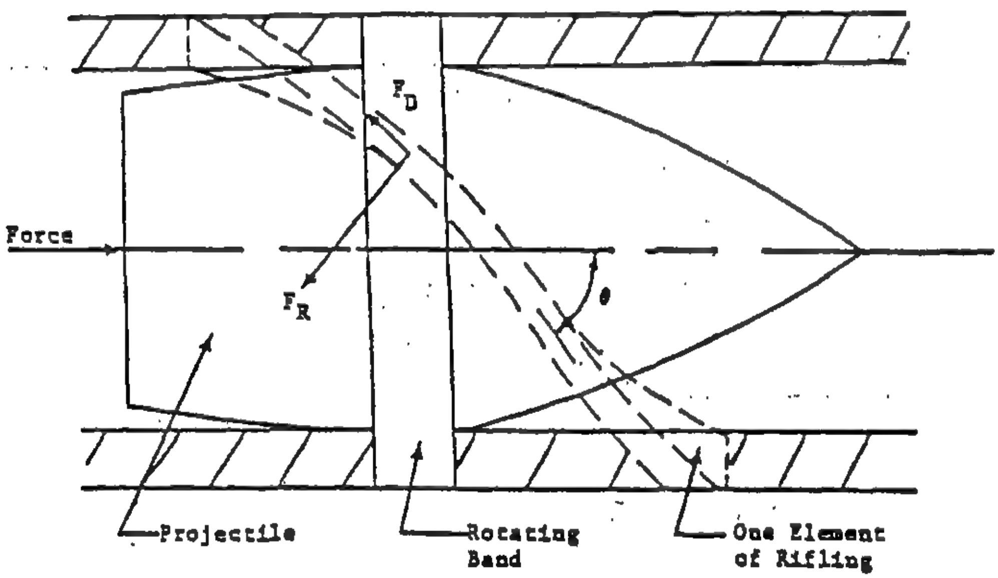
Projectile Dynamic Motions :

Sliding, Rotating, and Engraving in the Gun Barrel

Force Balance :

Driving Force : Pressure Acting on Projectile Base

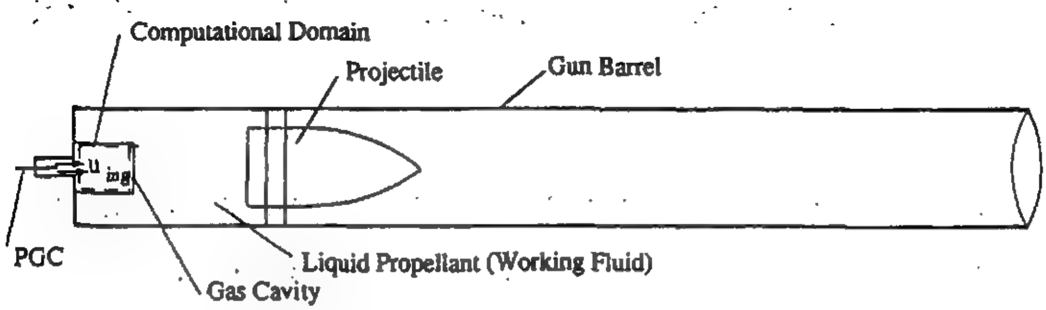
Resistant Forces : Due to Sliding, Rotating, and Engraving Motions



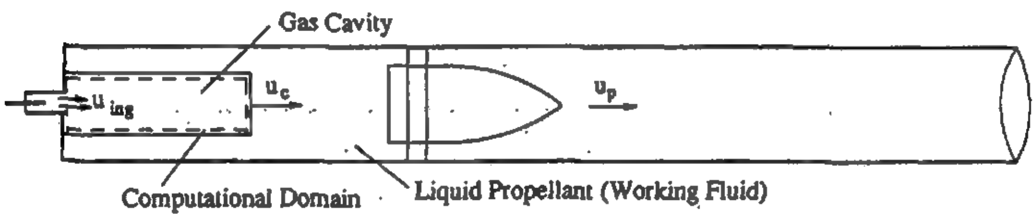
$$a_p = \frac{R_p^*\left[(P_B - P_\infty) A_{CS}(\cos\theta - C_f \sin\theta) - F_D'\right]}{W_p R_p^*(\cos\theta - C_f \sin\theta) + I_p K_p(\cos\theta + C_f \sin\theta)}$$

Numerical Solutions

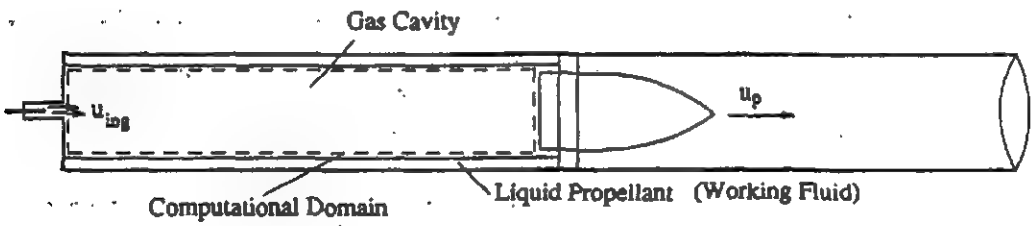
* Computational Domain



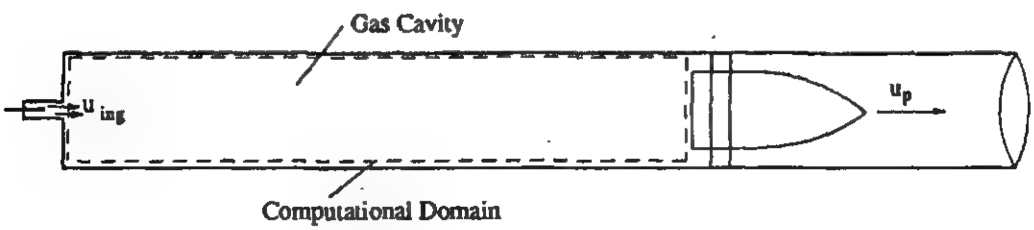
(a) Initial Stage of Firing Cycle



(b) Development of Taylor Cavity



(c) Annual Liquid Film Stage



(d) Free Expansion stage

Coordinate Transformation

Original Coordinate : t, x, r

New Coordinate : τ, η, ζ

$$\tau = t,\ \eta = x + u_c(t - t_o),\ \ \zeta = r + v_w(t - t_o)$$

$$\frac{\partial(\Phi\psi\rho_g)}{\partial t} = \frac{\partial(\Phi\psi\rho_g)}{\partial \tau} + u_c\frac{\partial(\Phi\psi\rho_g)}{\partial \eta} + v_w\frac{\partial(\Phi\psi\rho_g)}{\partial \zeta}$$

Algorithm

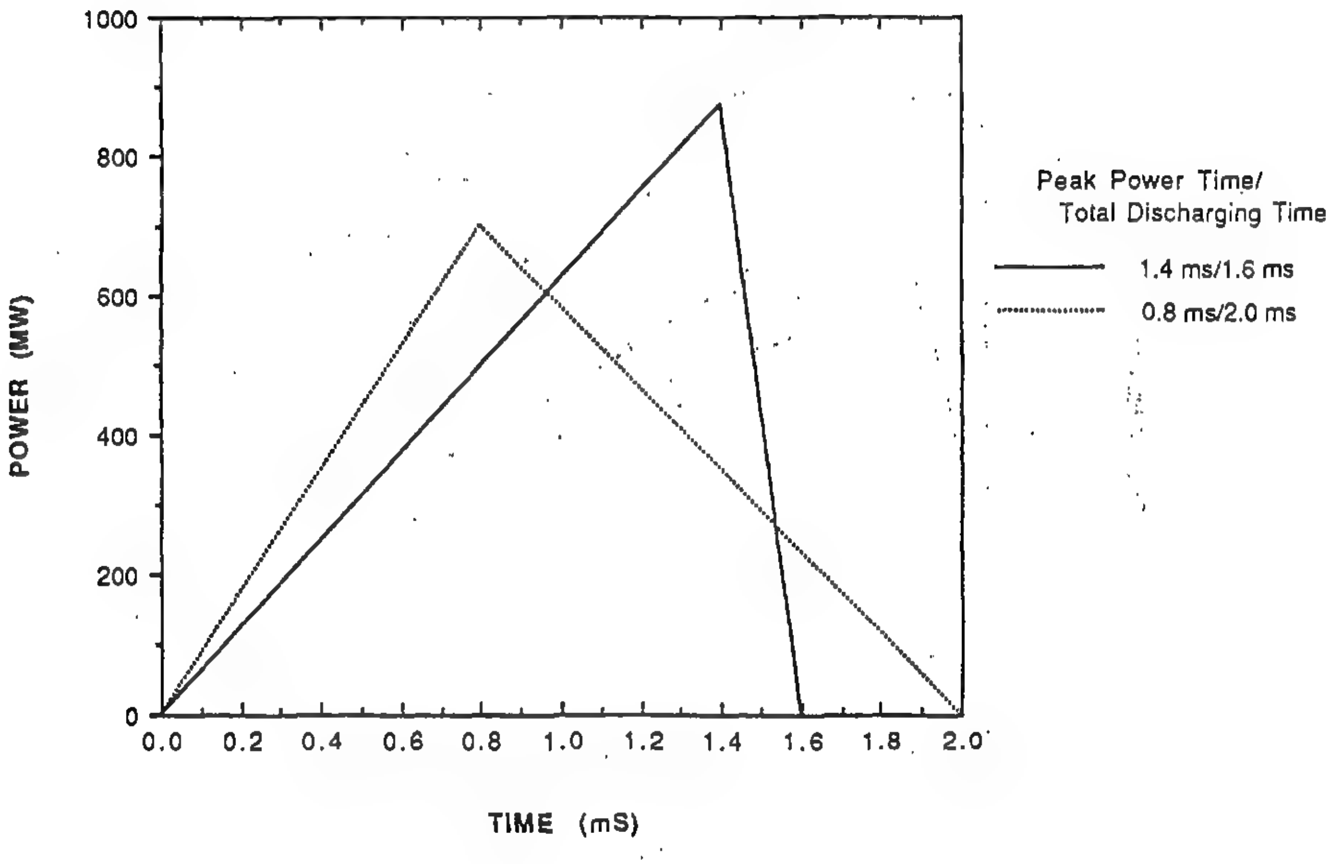
* SIMPLE (Semi-Implicit Method for Pressure-Linked Equations)

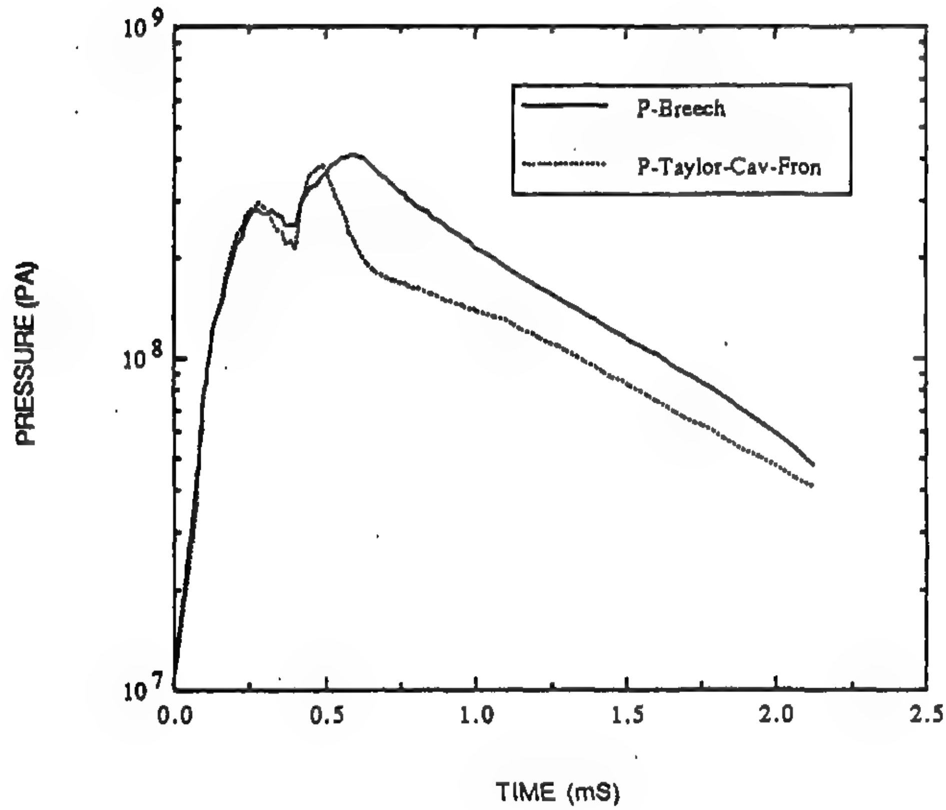
* Highly Compressible Flows :
  a. Density Variation Effects on Pressure Correction Equations
  b. Equation of State - Noble Abel Equation

*Pressure Correction Equation

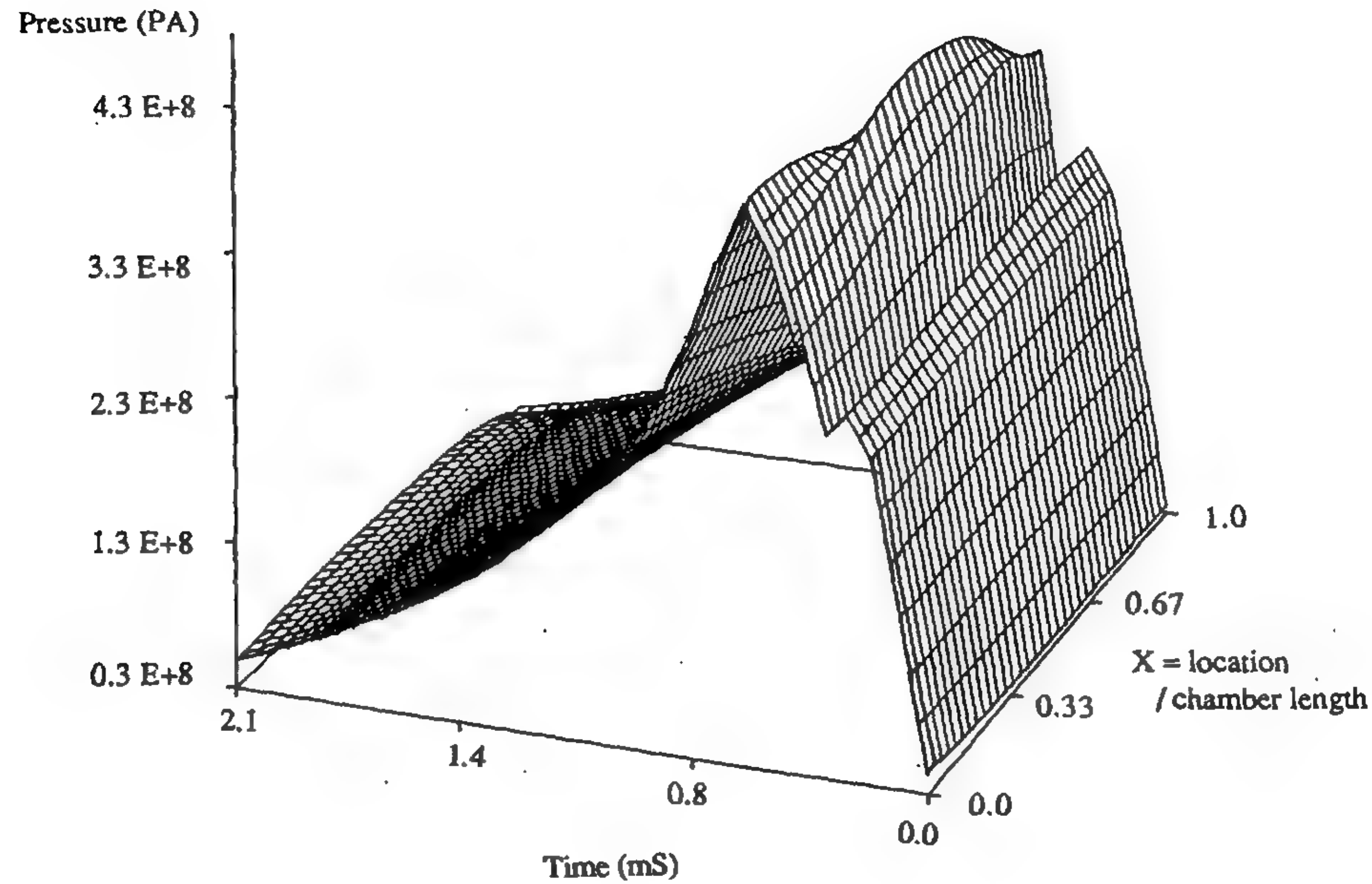
$$a_P P'_P = a_E P'_E + a_W P'_W + a_N P'_N + a_S P'_S$$

$$a_E = (\rho^*_e d_e - K u^*_e) A_\eta$$
$$a_W = (\rho^*_w d_w - K u^*_w) A_\eta$$
$$a_S = (\rho^*_s d_s - K u^*_s) A_\zeta$$
$$a_N = (\rho^*_n d_n - K u^*_n) A_\zeta$$
$$a_P = (\rho^*_n d_n + \rho^*_s d_s) A_\zeta + (\rho^*_e d_e + \rho^*_w d_w) A_\eta + \frac{K\ \Delta V}{\Delta t}$$
$$d_j = \frac{A_j}{a_j} \quad j = e, w, s, n$$
$$K = \frac{R\,T_g}{(Pb + RT_g)^2}$$

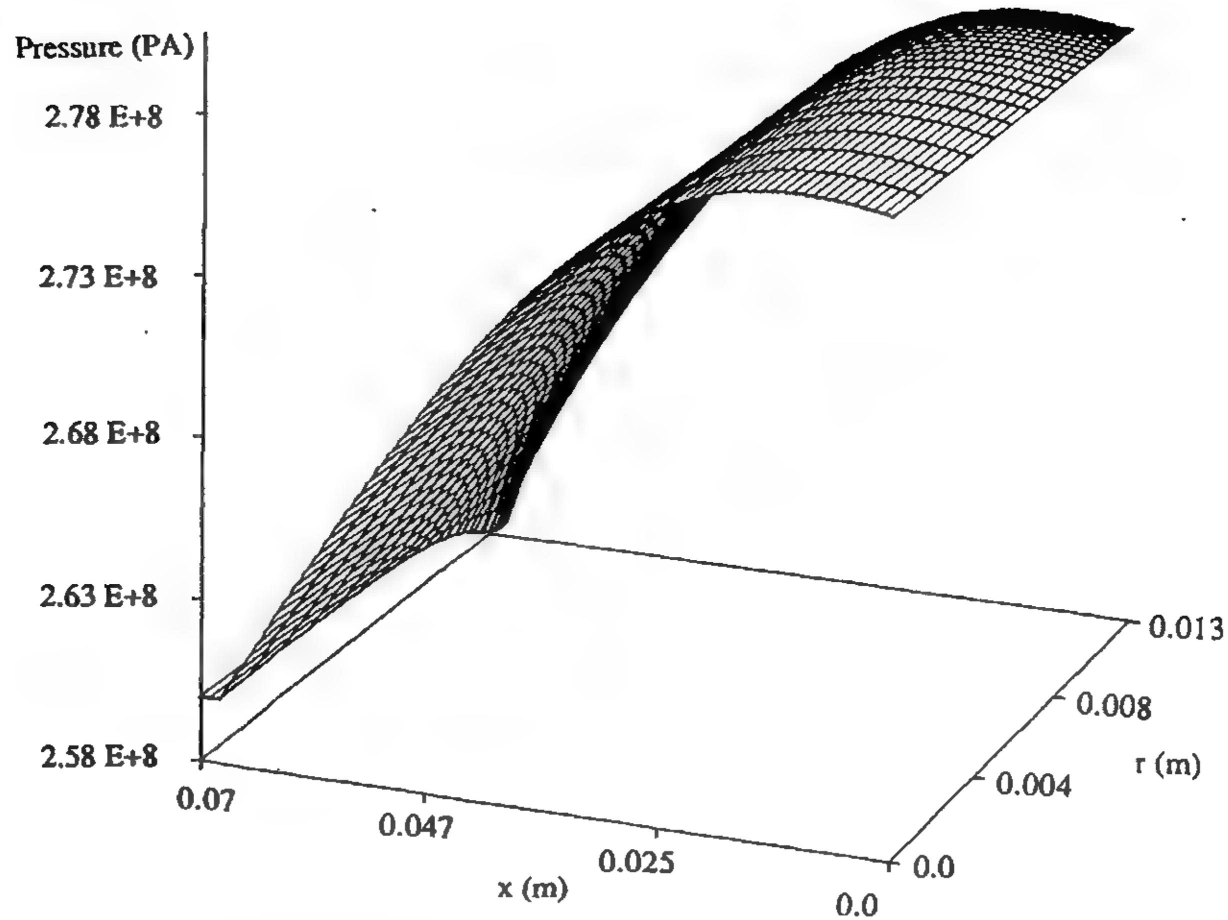

1000
800
600
400
200
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
POWER (MW)
TIME (mS)
Peak Power Time/
Total Discharging Time
1.4 ms/1.6 ms
0.8 ms/2.0 ms



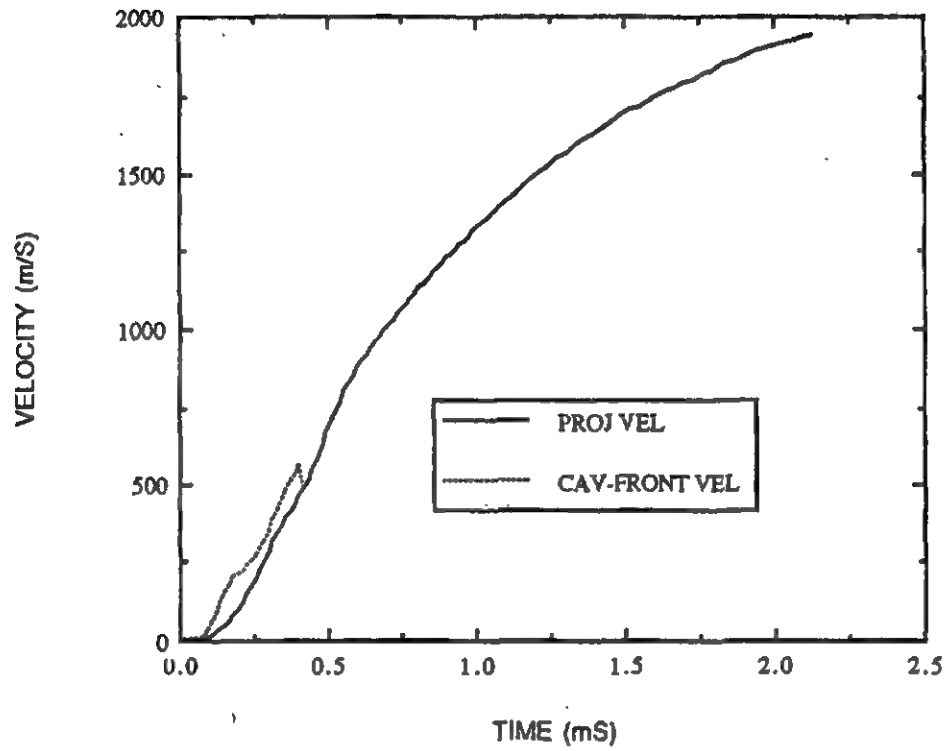
Breech and Taylor Cavity Front Pressure-Time Traces with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



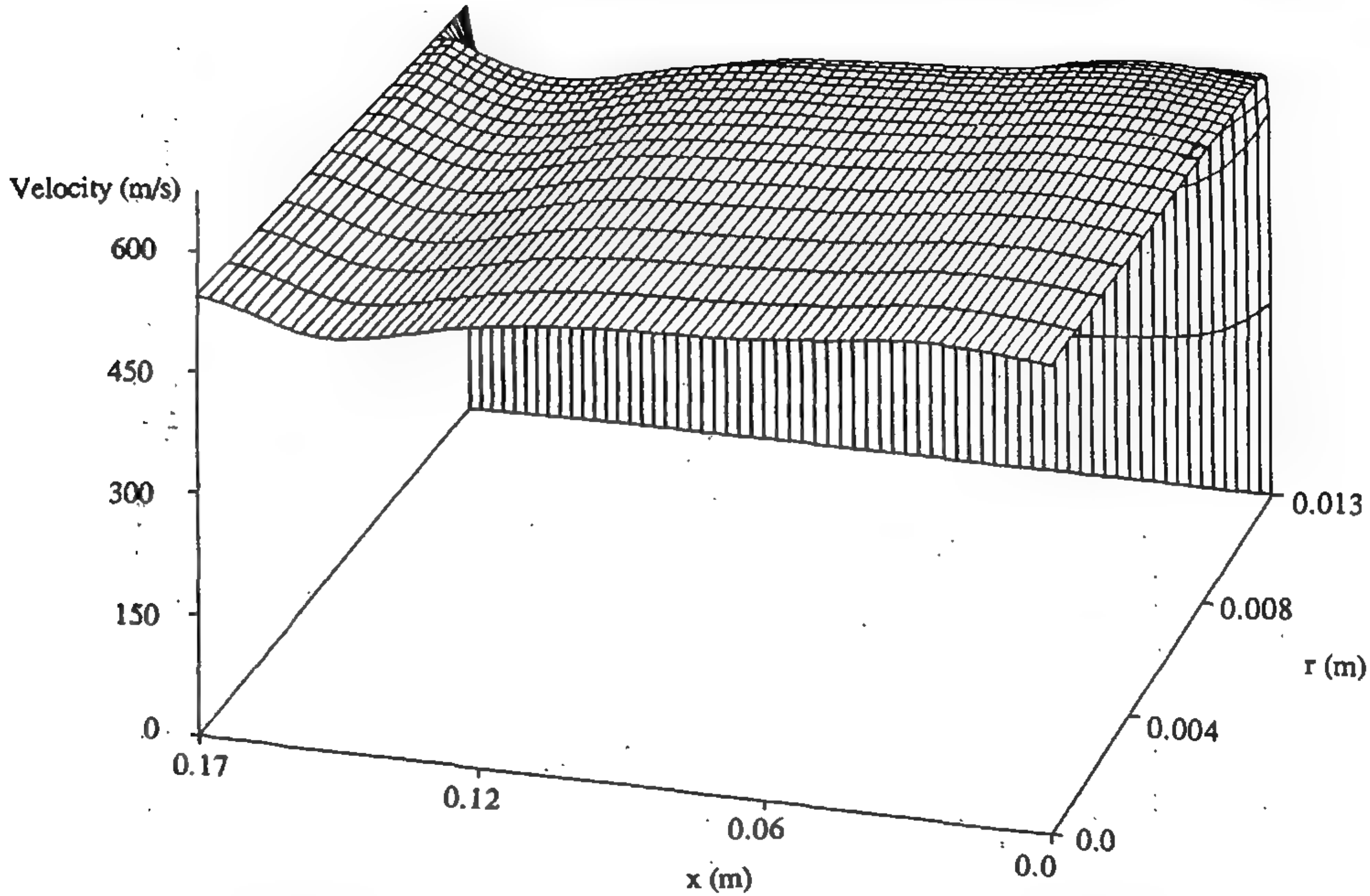
Time History of Averaged Axial Pressure in the ET Gun Chamber with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



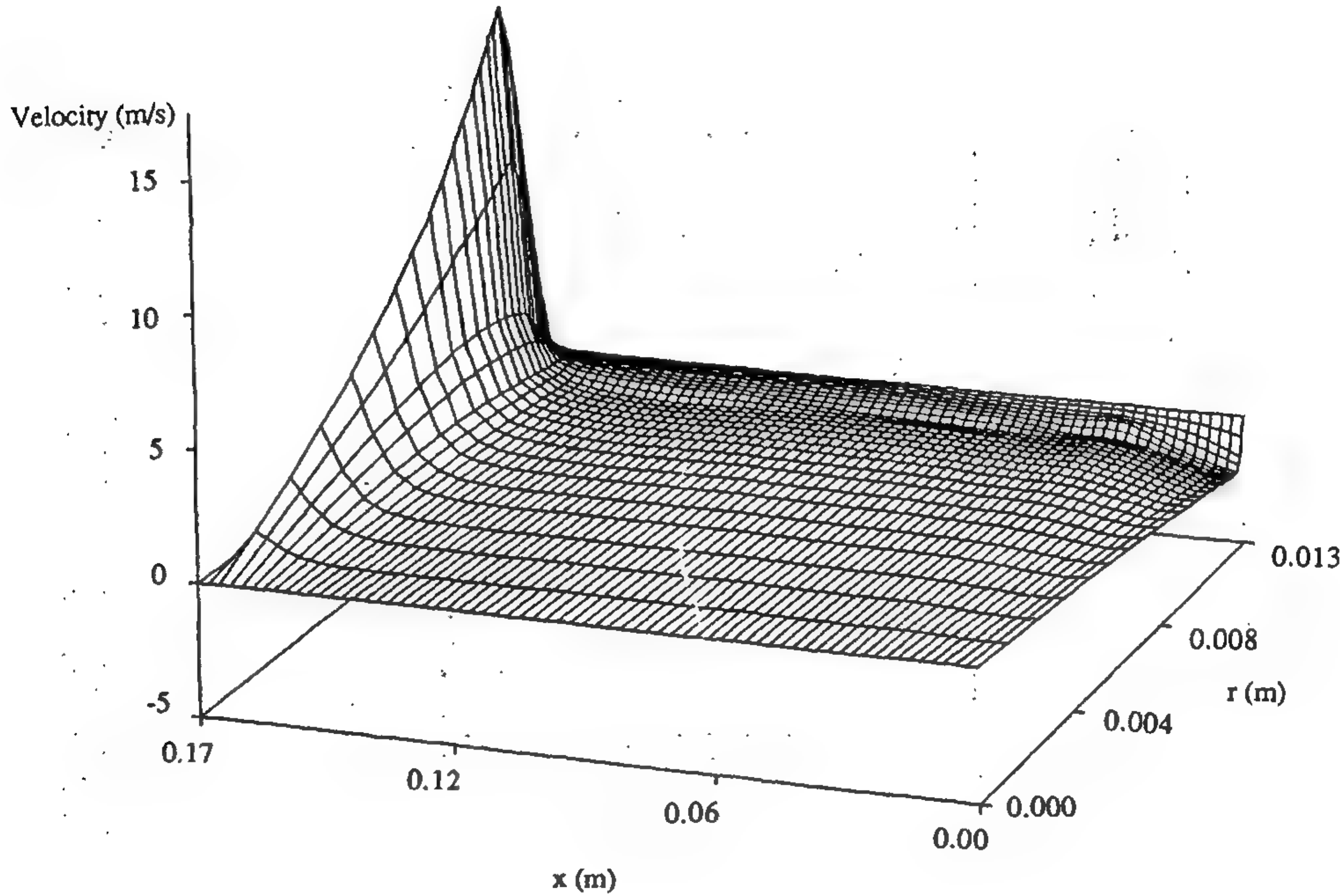
Spatial Pressure Distribution in the ET Gun Chamber at 0.33 ms with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



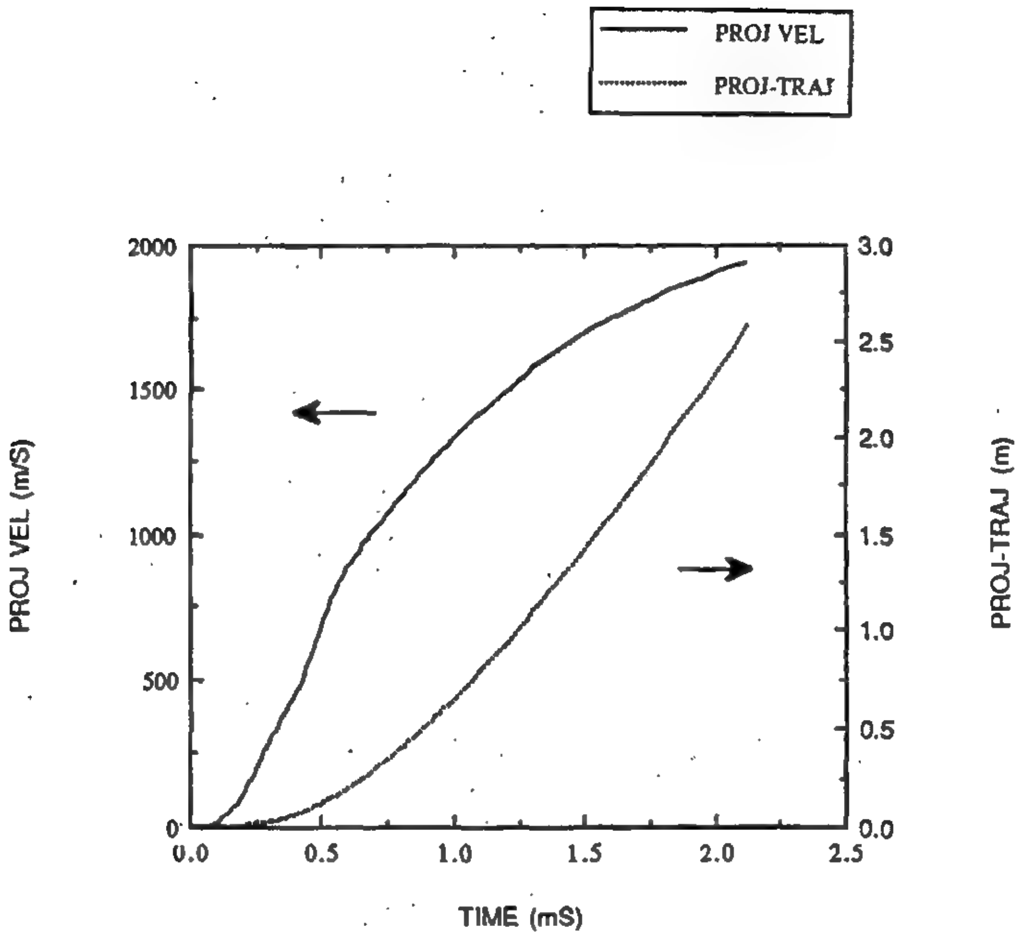
Projectile and Taylor Cavity Frontal Velocity-Time Traces with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



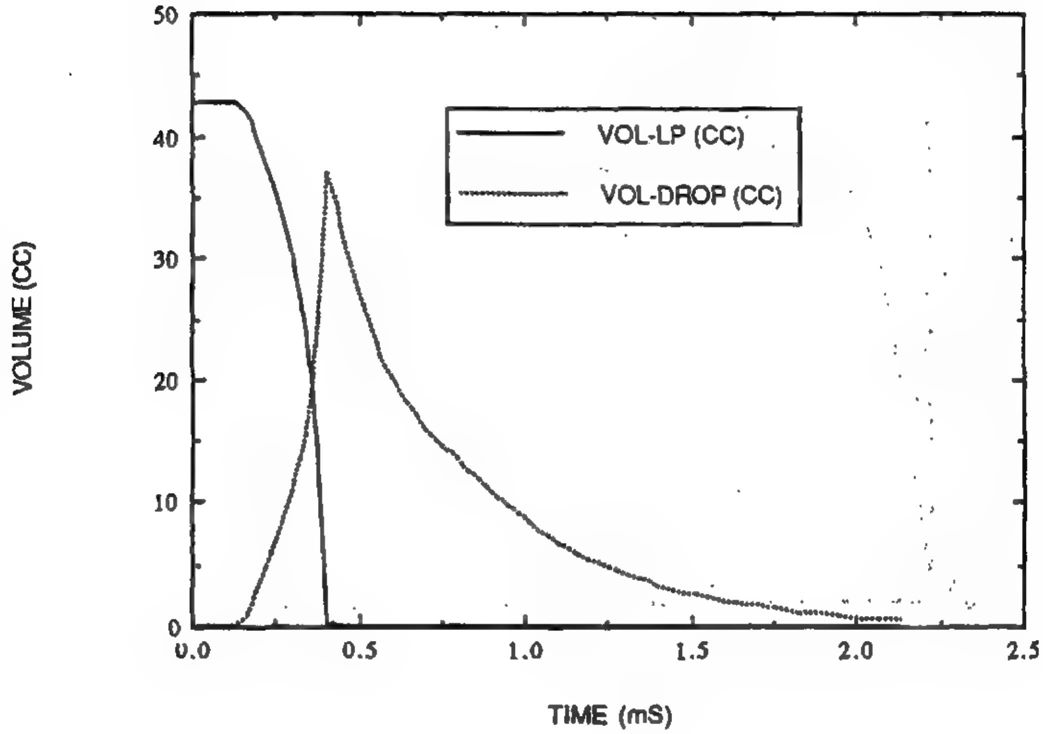
Spatial Distribution of Axial Gas Velocity in the ET Gun Chamber at 0.45 ms
with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



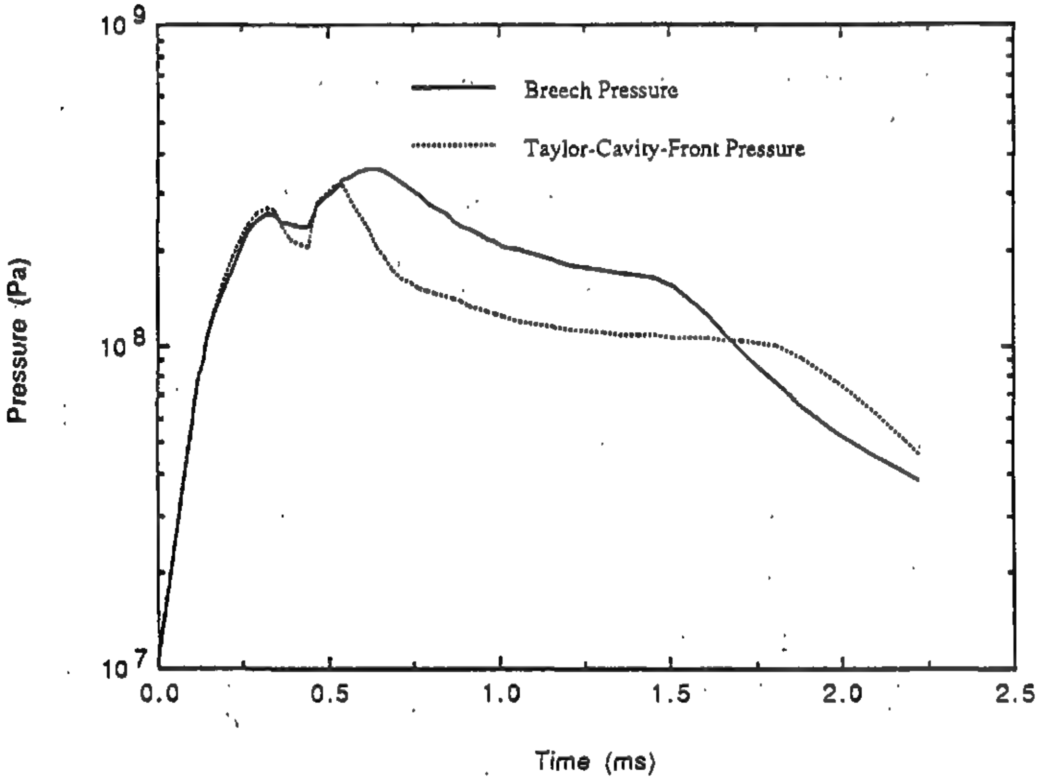
Spatial Distribution of Radial Gas Velocity in the ET Gun Chamber at 0.45 ms
with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



Projectile Trajectory and Velocity-Time History with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms

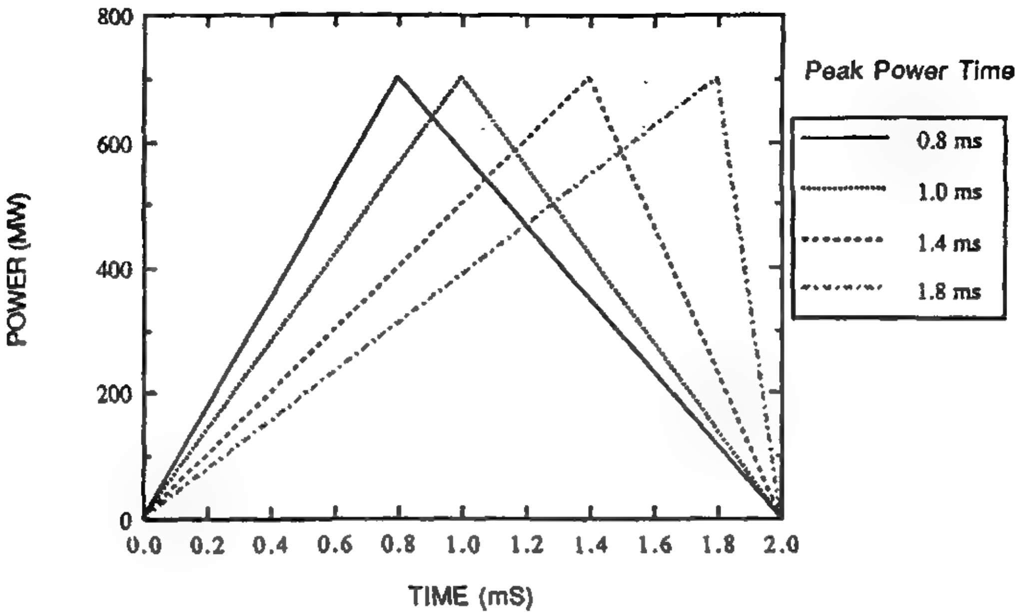


Liquid Propellant and Droplet Volume-Time Traces with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms

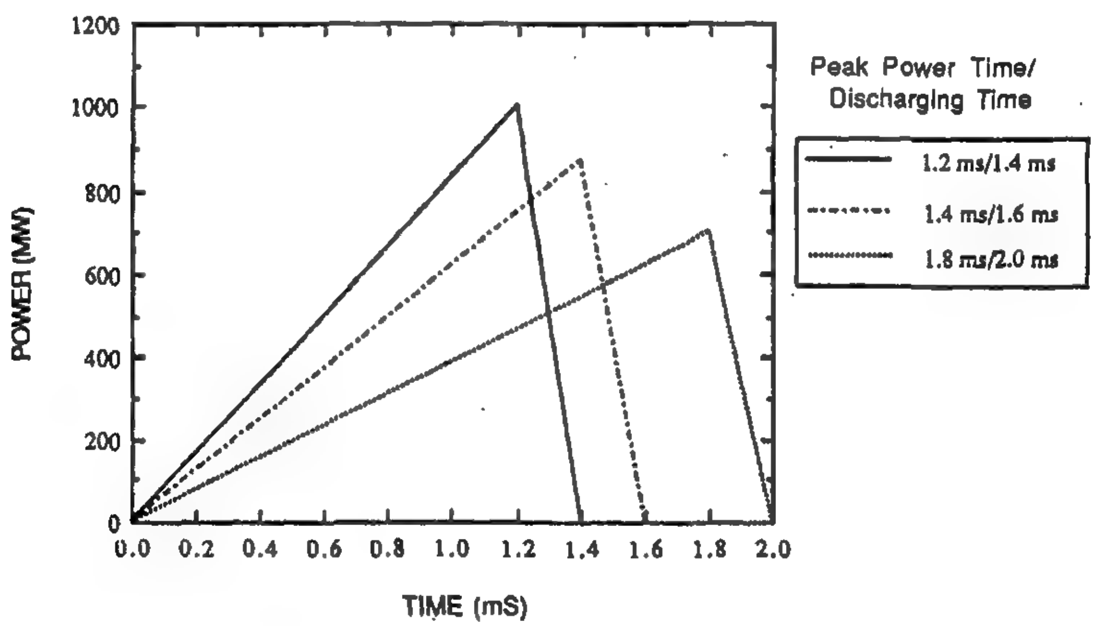


Breech and Taylor Cavity Front Pressure-Time Traces with PFN Peak Power Time at 1.4 ms and Discharging Time of 1.6 ms

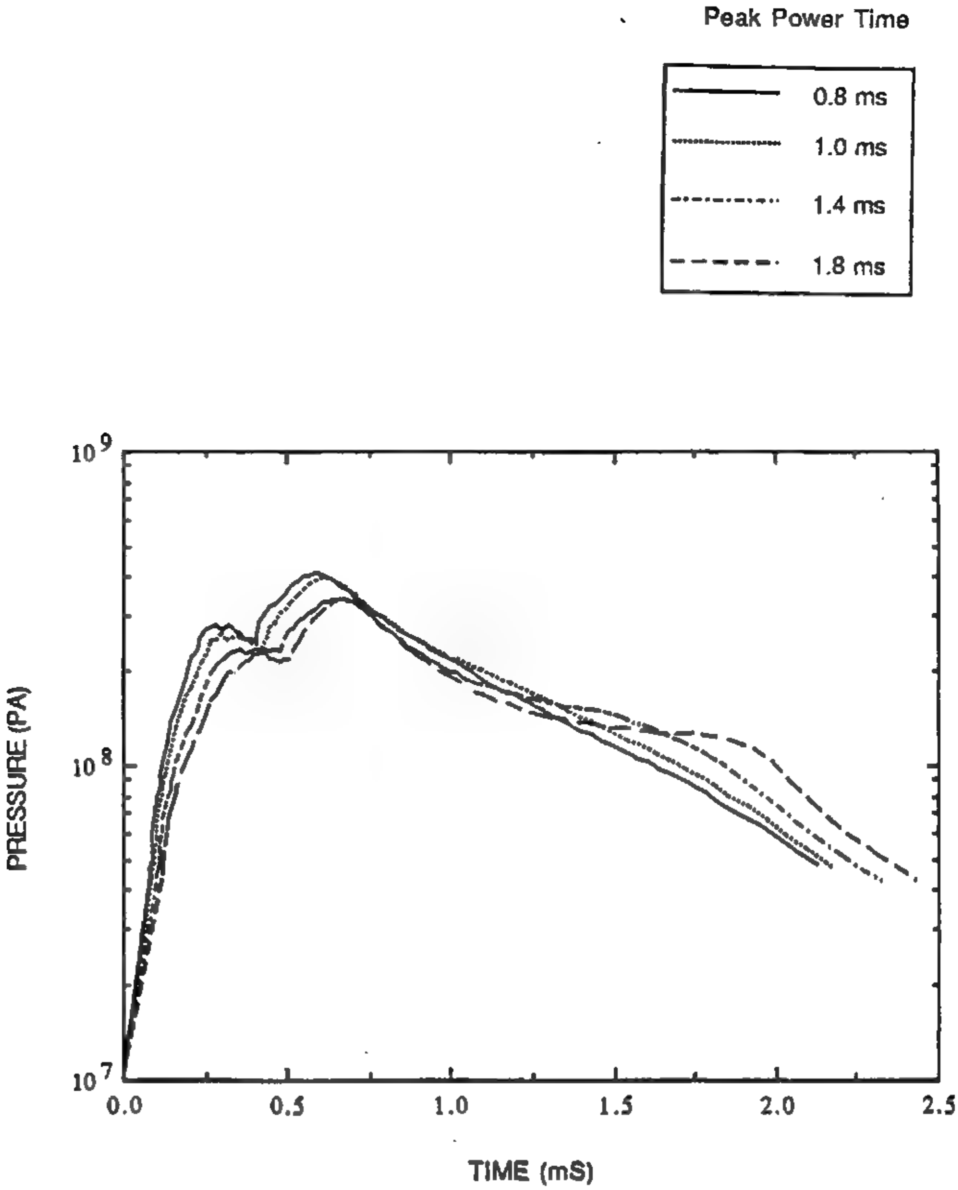
(a) Various Peak Power Times



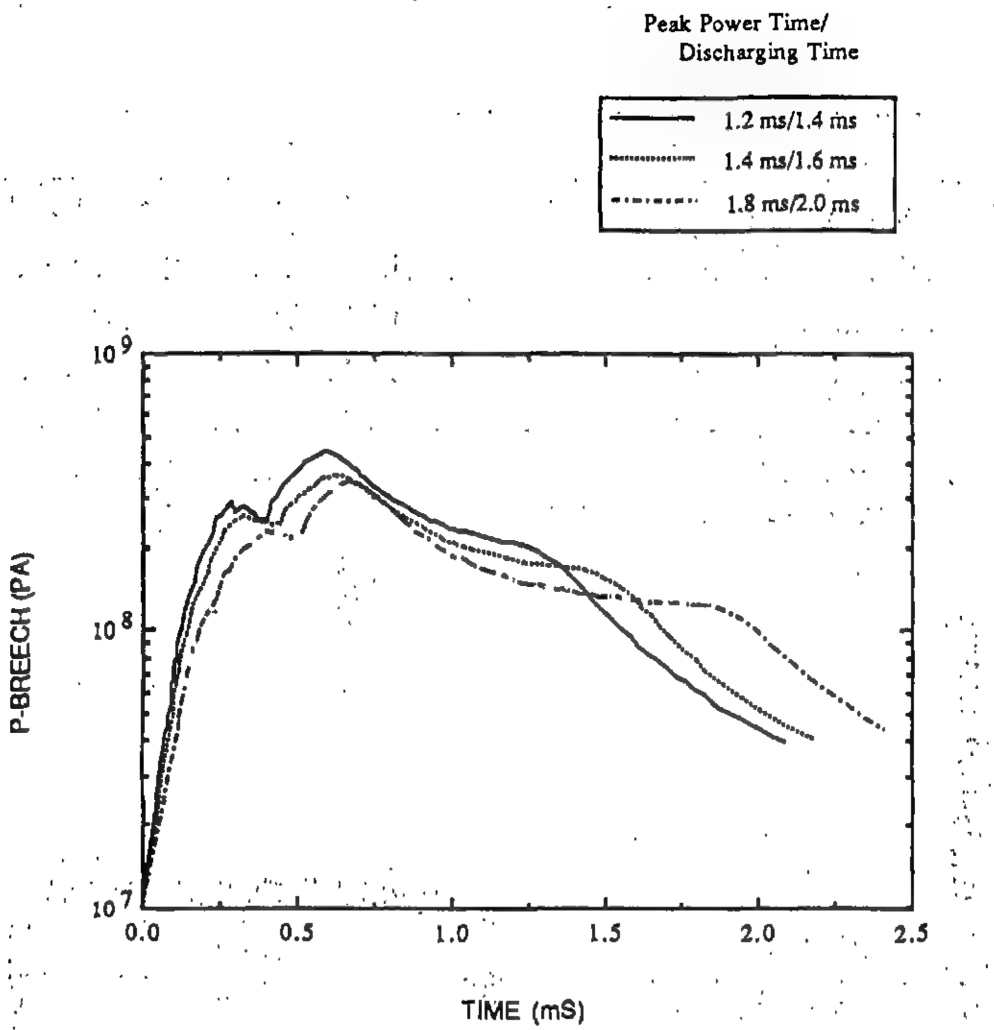
(b) Various Total Discharging Times



PFN Discharging Power Curves with (a) Various Peak Power Times and (b) Various Total Discharging Times



Breech Pressure-Time History Traces with PFN Discharging Time of 2.0 ms and Various Peak Power Times



Breech Pressure-Time Traces for Various PFN Total Discharging Times and Peak Power Times

Results from Numerical Analysis for Cases with
Various Peak Power Times

PFN Discharging Characteristics		Interior Ballistic Data			
Peak Power Time (ms)	Total Discharging Time (ms)	Event Time (ms)	Maximum Breech Pressure (PA)	Muzzle Velocity (m/s)	Ballistic Efficiency
0.8	2.0	2.11	$4.10*10^{8}$	1936	12.0 %
1.0	2.0	2.18	$3.95*10^{8}$	1924	11.8 %
1.4	2.0	2.32	$3.40*10^{8}$	1882	11.0 %
1.8	2.0	2.43	3.39*108	1822	10.6 %

*Electrical Energy 0.7 MJ, Chemical Energy 0.4 MJ

Results from Numerical Analysis for Cases with
Total Discharging Times

PFN Discharging Characteristics		Interior Ballistic Data			
Peak Power Time (ms)	Total Discharging Time (ms)	Event Time (ms)	Maximum Breech Pressure (PA)	Muzzle Velocity (m/s)	Ballistic Efficiency
1.2	1.4	2.08	$3.60*10^{8}$	2048	13.3 %
1.4	1.6	2.22	$3.40*10^{8}$	1972	12.4 %
1.8	2.0	2.43	3.39*108	1822	10.6 %

*Electrical Energy 0.7 MJ, Chemical Energy 0.4 MJ

Interior Ballistic Results from Present Work and Literature

(a) Measured Results

Source	Gun (mm)	Barrel (caliber)	Projectile Mass (gm)	Muzzle Vel (km/S)	Electrical Eng (kJ)	Working Fluid	Electrical+ Efficiency	Ballistic+ Efficiency	Max Breech P (psi)
Greig et al (1988)	20	100	8	3.5	700	*	7%	*	*
Greig et al (1988)	20	100	21	2.8	700	*	11.8%	*	55,000 - 74,000
Greig et al (1988)	20	100	50	2.1	700	*	15.7%	*	*
Greig et al (1988)	30	100	102	1.43	2000	*	5.2%	*	*
Chryssom-allis (1988)	10	*	1 - 6.5	1.2 - 1.7	190 - 325	exothermic propellant	25 - 40%	*	30,000 - 40,000
Chryssom-allis (1988)	30	85	50 - 380	1.1 - 2.75	240 - 850	exothermic propellant	25 - 90%	*	45,000 - 75,000
Chryssom-allis (1988)	90	*	1100 - 1200	1.0 - 1.3	800 - 1100	exothermic propellant	75 - 95%	*	20,000 - 35,000
Chryssom-allis (1988)	105	*	2000 - 6000	0.7 - 1.5	1000 - 4000	exothermic propellant	90 - 130%	*	20,000 - 40,000

* Data Unavailable +Electrical Efficiency = Projectile Kinetic Energy / Input Elecurical Energy
Ballistic Efficiency = Projectile Kinetic Energy / Total Input Energy

(b) Predicted Results

Source	Gun (mm)	Barrel (caliber)	Projectile Mass (gm)	Muzzle Vel (km/s)	Working Fluid	Electrical Engy (kJ)	Total Engy (kJ)	Electrical Efficiency	Ballistic Efficiency
Oberle (1988)	14	100	18	2.17	H_2O	447.8	368.6	9%	10.9%
Oberle (1988)	14	100	18	2.34	$LiBH_4$	449.8	406.4	10.9%	12.1%
Oberle (1988)	14	100	18	1.75	TiH_2/Al	77.9	222.2	35.6%	12.5%
Oberle (1988)	14	100	18	2.13	C_8H_{18}/H_2O_2	43.3	322.6	94.2%	12.6%
Present Work+	25	100	70	1.94 - 2.05	C_8H_{18}/H_2O_2	700	1100	18.7 - 21.0%	10.6 - 13.3%

\+ Max Breech Pressure = 52,900 - 60,200 psi. Gun System Information: Projectile Mass = 70 gm, Residual Air = 5%, Chamber Length/Diameter = 3.5, Electrical Energy = 0.7 MJ, Total Energy = 1.1 MJ, Working Fluid = C_8H_{18}/H_2O_2

Conclusions

1. A comprehensive theoretical model describing the interior ballistic processes of an ET gun has been formulated.

2. The effects of PFN discharging characteristics on gun performance have been identified.

3. Muzzle velocity can be optimized by tailoring the PFN discharging time and peak power time while holding a moderate maximum breech pressure.

INTENTIONALLY LEFT BLANK.

FINITE-ELEMENT MODELING OF ELECTROTHERMAL-CHEMICAL GUNS

N. K. Winsor and S. A. Goldstein
GT-Devices, Inc.
Alexandria, VA 22312

ABSTRACT

Two-dimensional modeling of reactive flow dynamics in an electrothermal cartridge is described and illustrated. Special emphasis will be placed on the effects of ullage and rate-dependent chemistry on large-scale wave dynamics.

1991 JANNAF ETC Modeling Workshop

FINITE-ELEMENT MODELING OF ELECTROTHERMAL-CHEMICAL GUNS

N. K. WINSOR & S. A. GOLDSTEIN

GT-DEVICES, INC.

A subsidiary of General Dynamics Land Systems

5705A General Washington Drive

Alexandria, VA 22312-2408

703-642-8150

SPECIAL THANKS TO:

Simon Wang

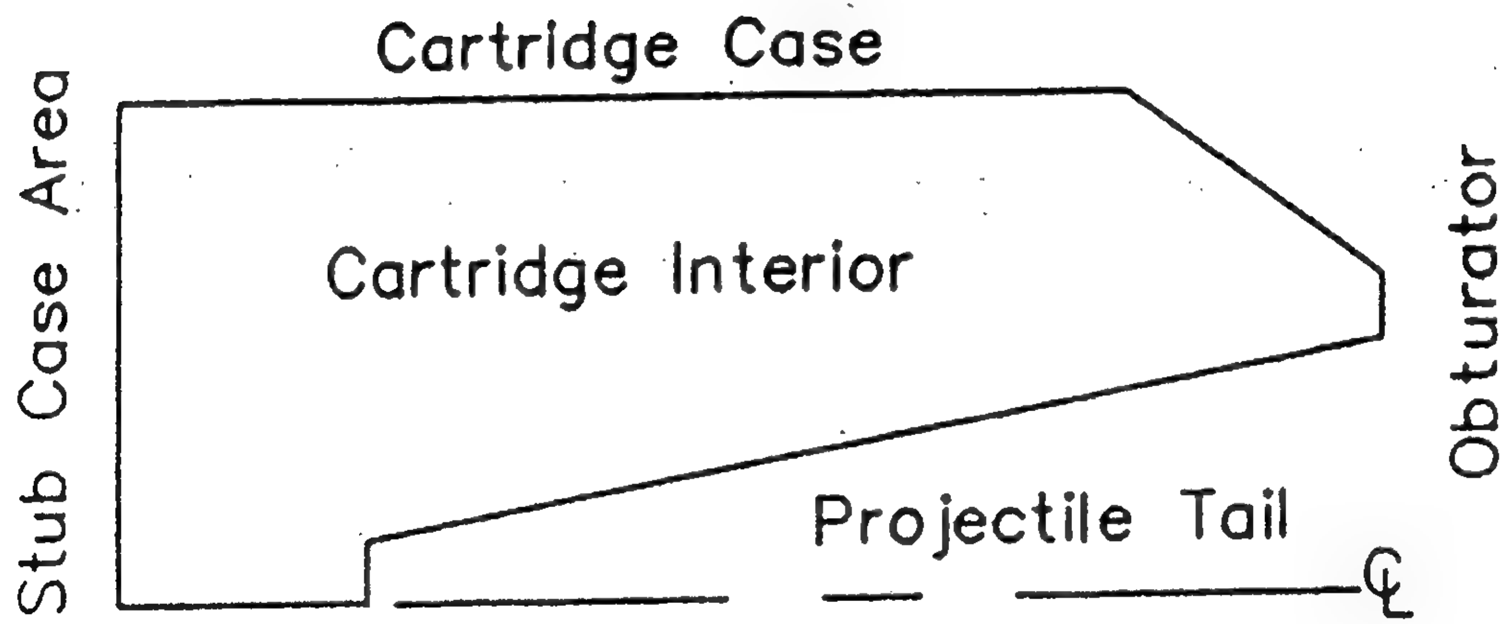
Bob Greig

Hugh McElroy

Steven Bunte

William Oberle

CARTRIDGE GEOMETRY



180

GT - Devices

GENERAL DYNAMICS
Land Systems Division

OUTLINE

FINITE-ELEMENT MODEL

WATER HAMMER TESTS

CLOSED BOMB EXPTS.

IBHVG2 #6 SIMULATION

SUMMARY

1. WATER HAMMER: SOUND SPEED DEPENDENCE ON PRESSURE IS KEY TO DYNAMICS OF ELECTROTHERMAL AND LIQUID PROPELLANT GUNS.

2. CLOSED BOMB: AN IDEAL METHOD FOR VALIDATING BURN MODELS.

3. IBHVG2 TEST: UNSTRUCTURED FINITE-ELEMENT METHODS WORK SPECTACULARLY IN GUN GEOMETRY!

FINITE-ELEMENT ETC MODEL (FETC)

NAVIER-STOKES EQ. OF MOTION

4th TIME, 2nd SPACE FCT ALG.

UNSTRUCTURED FINITE-ELT. GRID

DETAILED CARTRIDGE GEOMETRY

DETAILED PROPELLANT CHEMISTRY

NAVIER–STOKES

TRANSPORT EQUATIONS

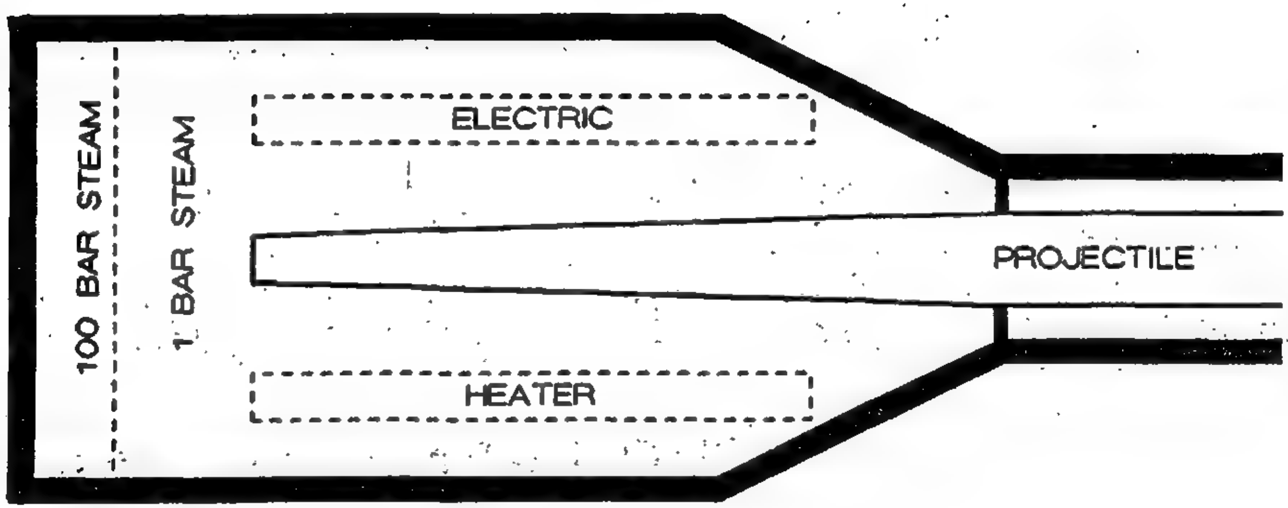
$$\frac{\partial U}{\partial t}+\frac{\partial F_a^x}{\partial x}+\frac{1}{r}\frac{\partial F_a^r}{\partial r} = \frac{S_a}{r}+\frac{\partial F_v^x}{\partial x}+\frac{1}{r}\frac{\partial F_v^r}{\partial r}+\frac{S_v}{r}$$

184

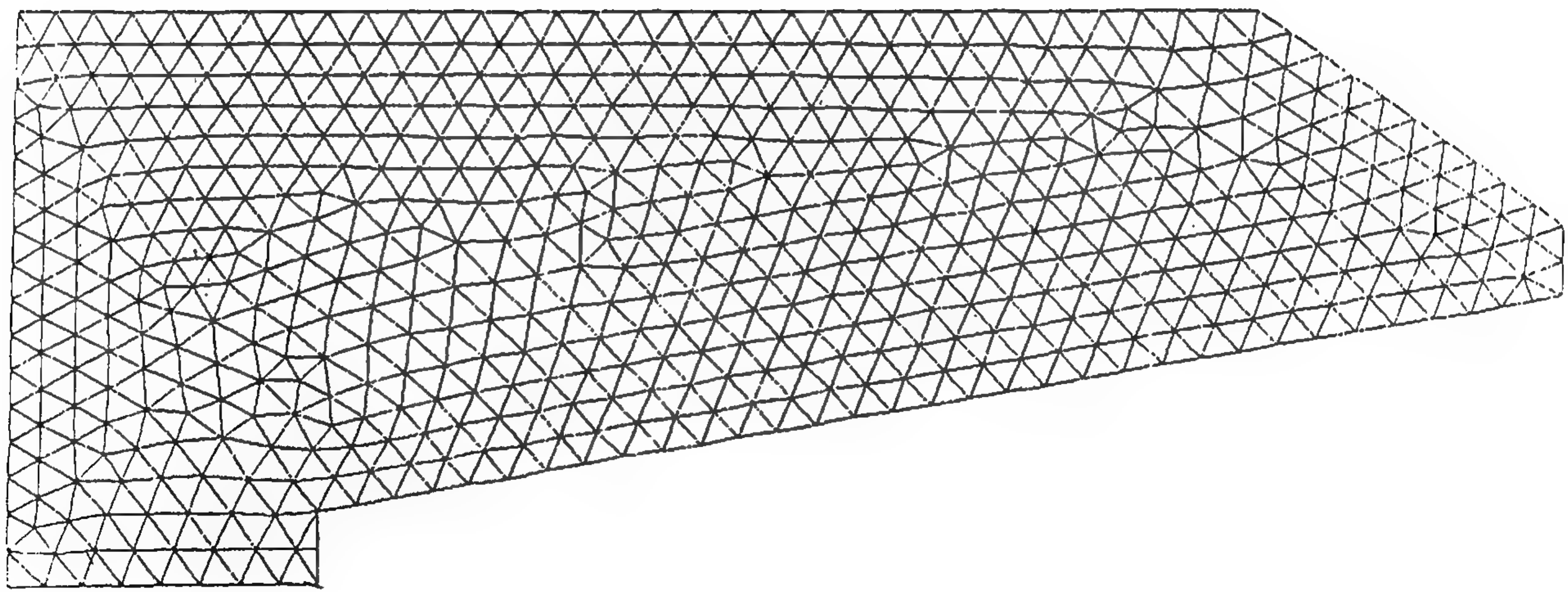
STATE VECTOR AND FLUXES

$$U = \begin{bmatrix}\rho \\ \rho u \\ \rho v \\ \rho e\end{bmatrix},\ F_a^x = \begin{bmatrix}\rho u \\ \rho u^2+p \\ \rho u v \\ uH\end{bmatrix},\ F_a^r = \begin{bmatrix} r\rho v \\ r\rho u v \\ r\rho v^2+rp \\ rvH\end{bmatrix},\ H = \rho e+p$$

SCHEMATIC GEOMETRY



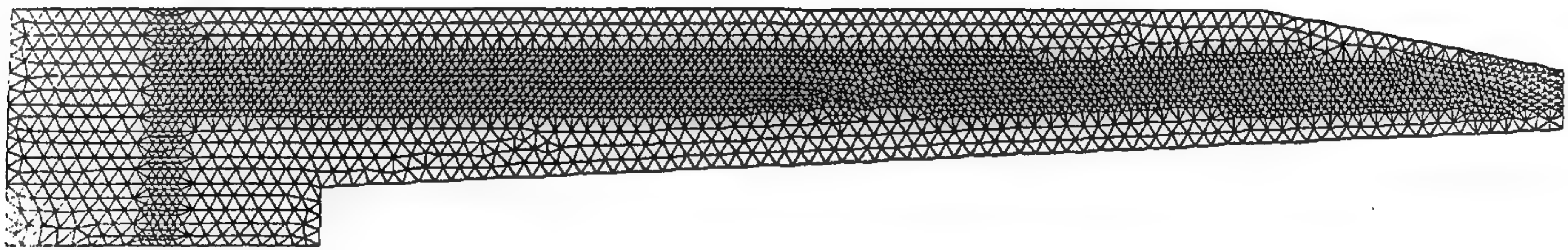
BASIC GRID STRUCTURE



GT - Devices

GENERAL DYNAMICS
Land Systems Division

SELECTIVELY-REFINED GRID



WATER HAMMER TESTS

WATER EQUATION OF STATE

COMBUSTIBLE STUB CASE "VOID"

PRESSURE WAVE -> SHOCK WAVE

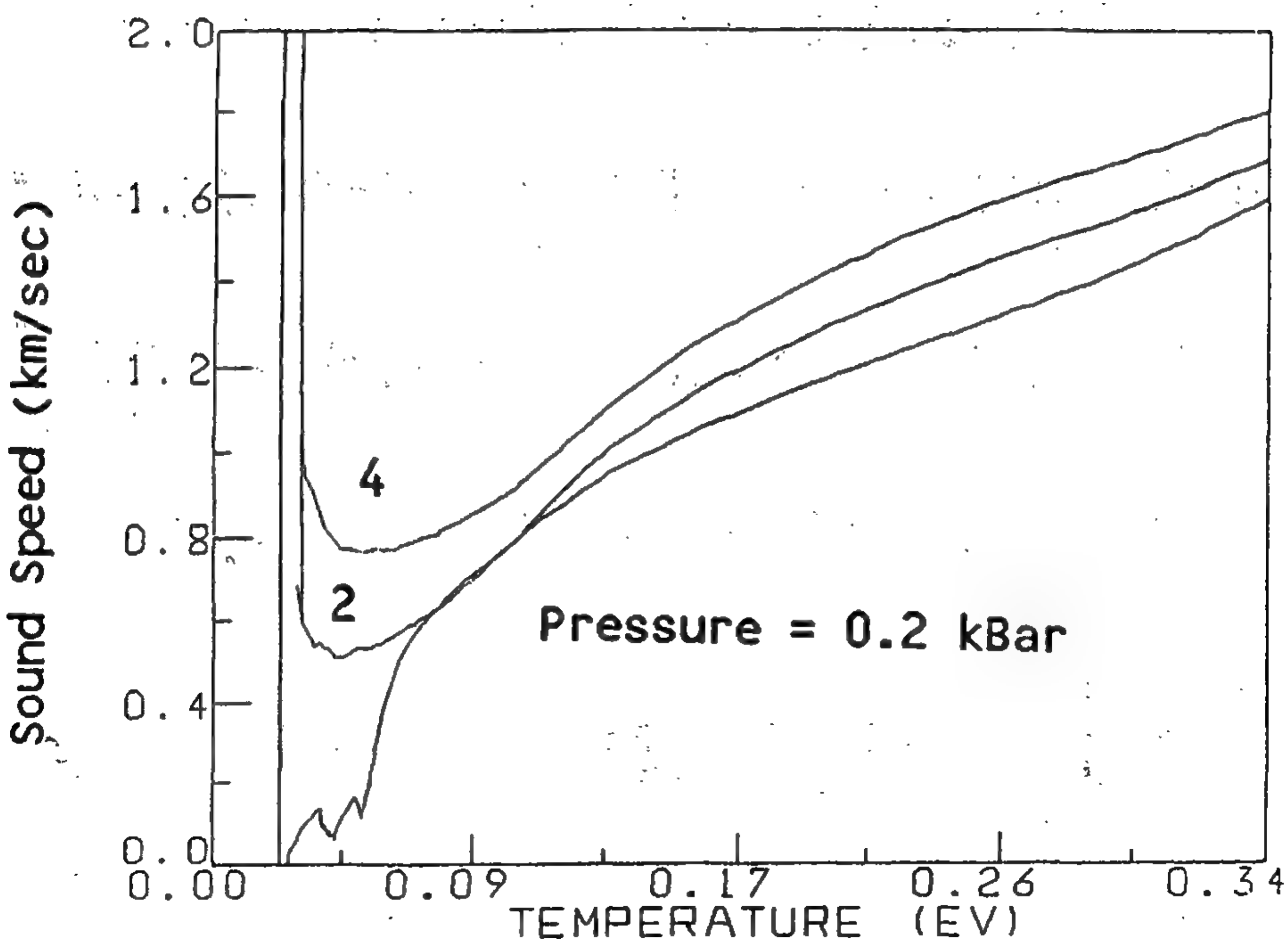
LARGE AMPLITUDE TRANSIENTS

HOW TO CONTROL THEM

GT - Devices

GENERAL DYNAMICS
Land Systems Division

SOUND SPEED VS. TEMPERATURE

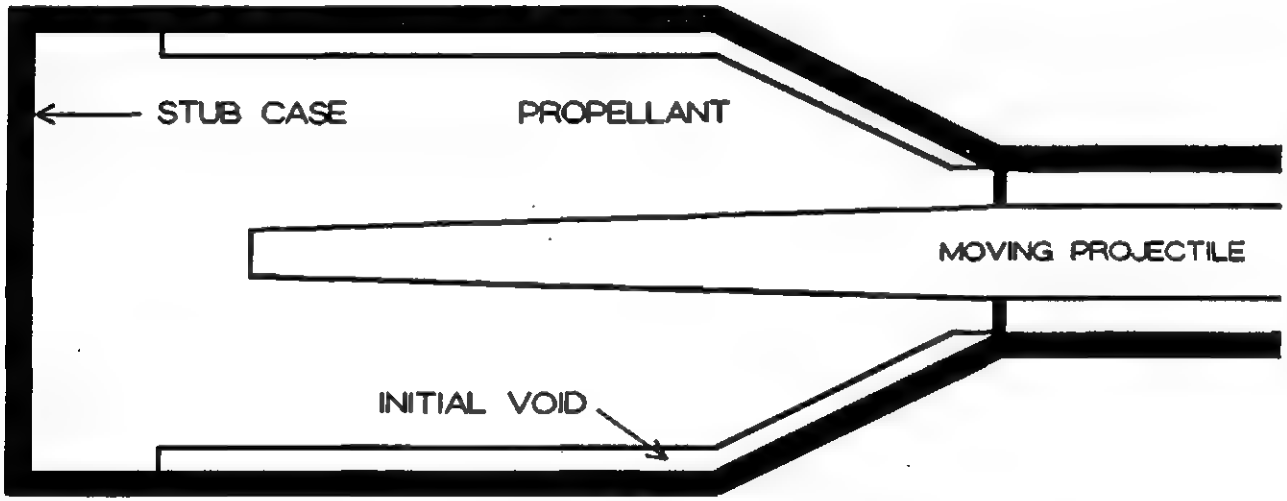


GT - Devices

GENERAL DYNAMICS
Land Systems Division

120mm GEOMETRY

COMBUSTIBLE CASE, VIEWED AS



INITIAL VOID, LIMITING SOUND SPEED.

SOUND SPEED

REDUCED BY:

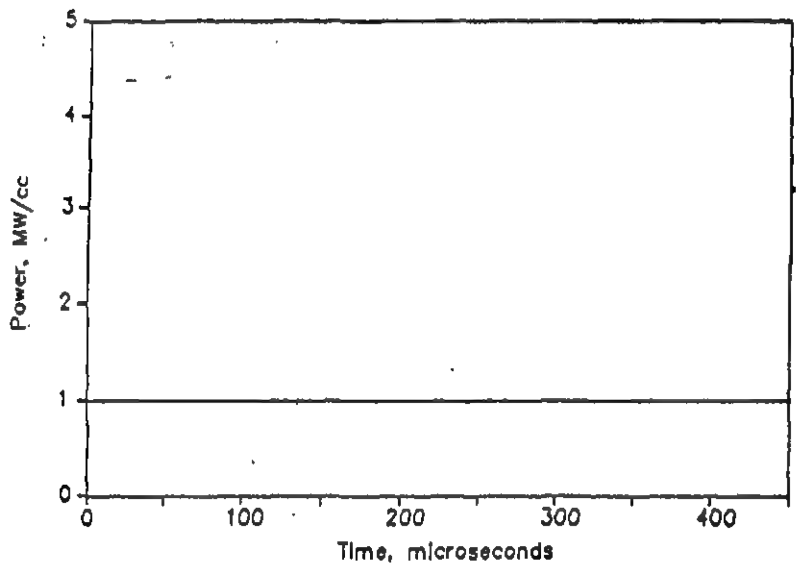
- LOW PRESSURE
- BUBBLES
- OTHER VOIDS

EFFECTS:

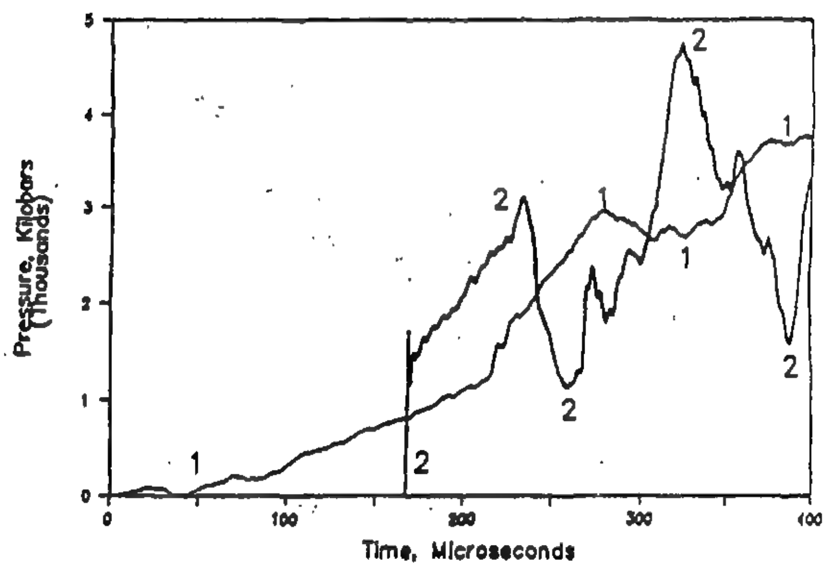
- SNOWPLOW SHOCK
- WATER HAMMER

CASE 1. UNIFORM POWER INPUT

POWER VS. TIME



PRESSURE VS. TIME



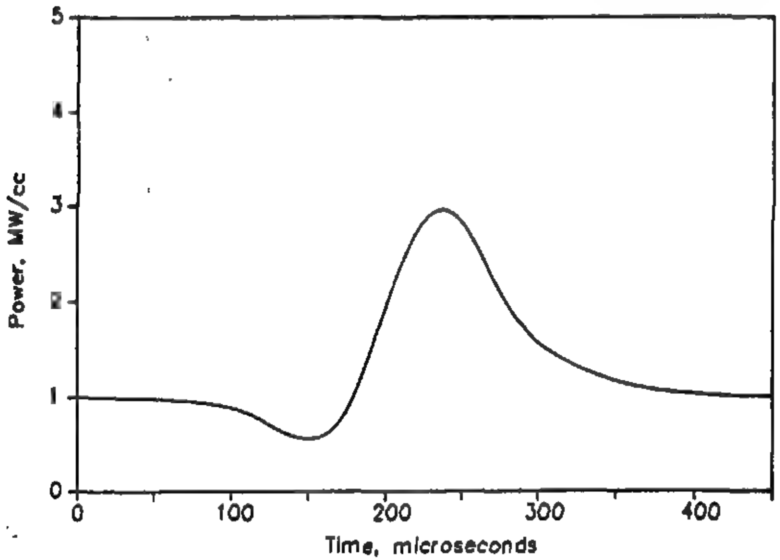
1 - IGNITER 2 - REFLECTOR

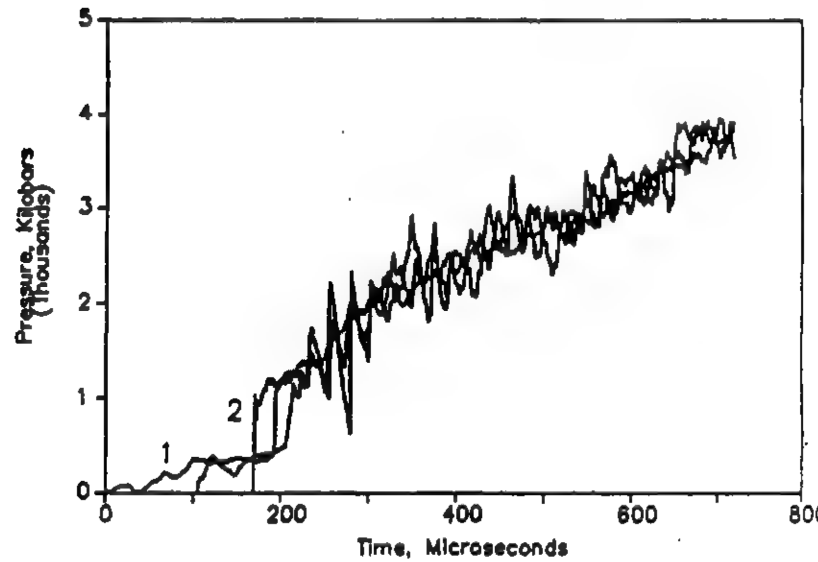
36A6023

GT-Devices

GENERAL DYNAMICS
Land Systems Division

CASE 2. TAILORED POWER DISTRIBUTION





1 – IGNITER 2 – REFLECTOR

36A6022

CONTROL OF TRANSIENTS

SEND A COMPRESSION WAVE

MINIMIZE THE SNOWPLOW

MEET THE REFLECTION

BE GENTLE!

CLOSED-BOMB EXPTS.

FIXED-WALL GEOMETRY

FULL MODEL CHEMISTRY

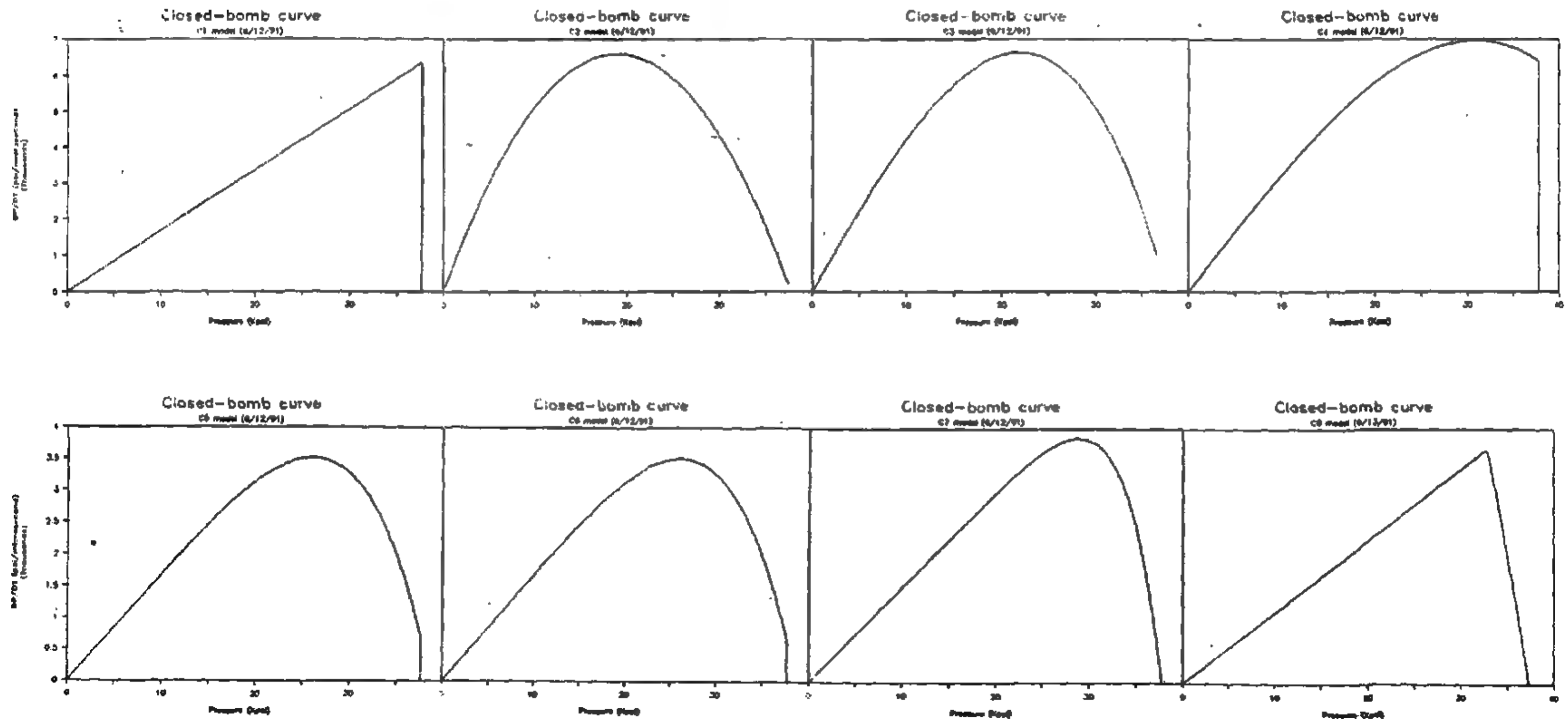
TRANSIENT COMBUSTION

MOVING-WALL GENERALIZATION

GT - Devices

GENERAL DYNAMICS
Land Systems Division

VARIOUS CLOSED-BOMB CURVES dP/dt VERSUS P



196

IBHVG2 TEST CASE #6

FEATURES INCLUDED:

- M829 LONG ROD PROJECTILE
- M125 PRIMER TUBE FLAME SPREAD
- JA2 COMBUSTION RATE

FEATURES OMITTED:

- PROPELLANT PERF GEOMETRY
- JA2 COMPRESSIBILITY IN EOS

RESULT:

- RELATIVELY COMPLETE SIMULATION

Temperature Sensitivity

Solid Propellant JA2
Experimental closed chamber burn rates at Ambient, at 50°C, and -32°C

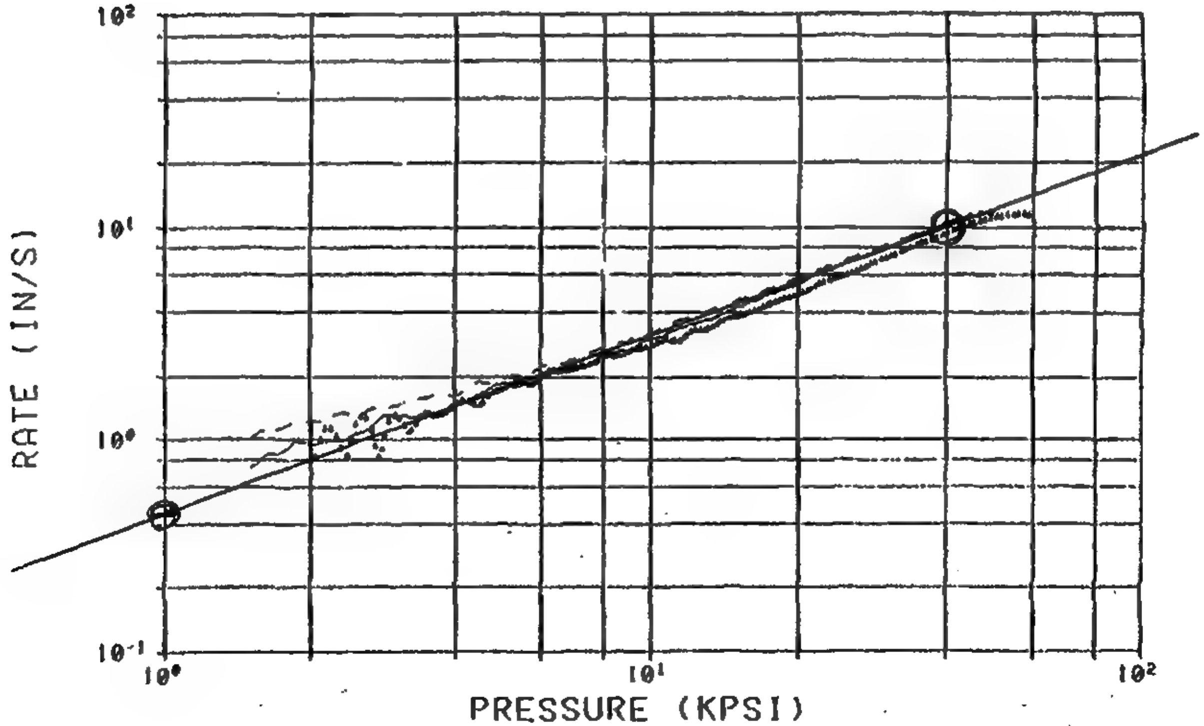
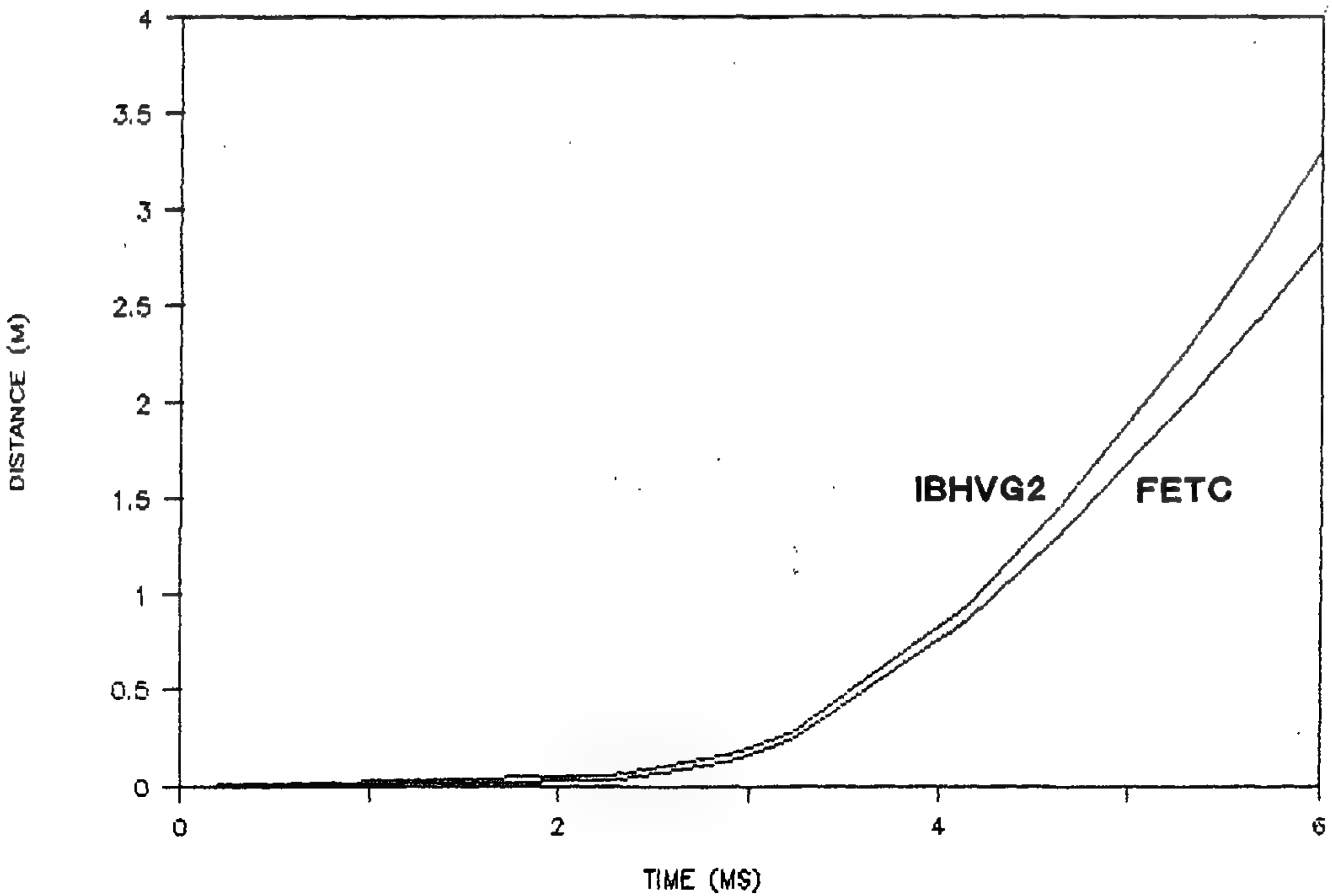


Figure 4. Comparison of Burning Rates at Ambient (——), at 50°C (-----), and at -32°C (ΔΔΔΔ).

120 MM SIMULATIONS COMPARED

IBHVG2 AND FETC PROJECTILE TRAVEL

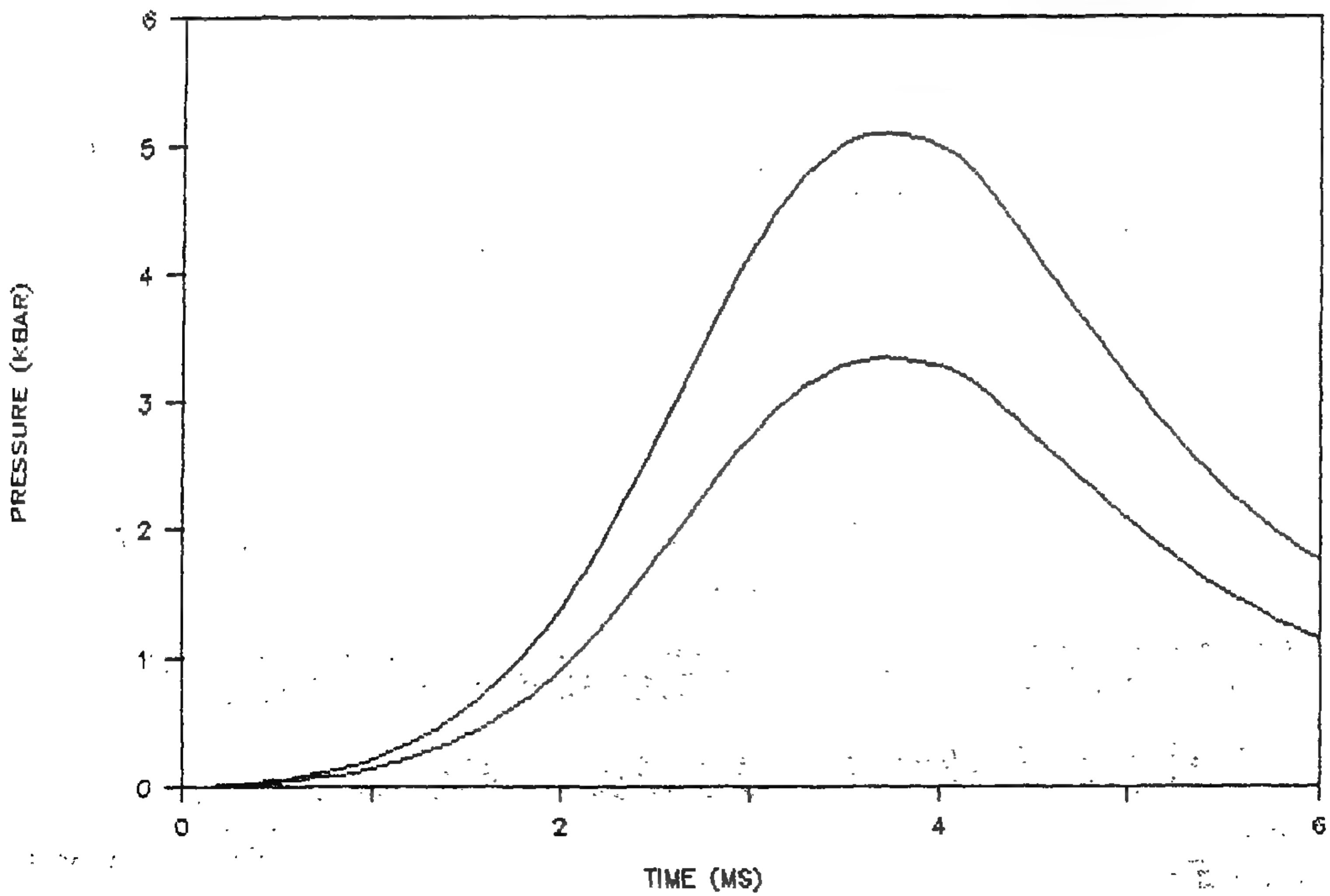


GT - Devices

GENERAL DYNAMICS
Land Systems Division

120 MM IBHVG2 SIMULATION

STUB AND PROJECTILE BASE PRESSURES

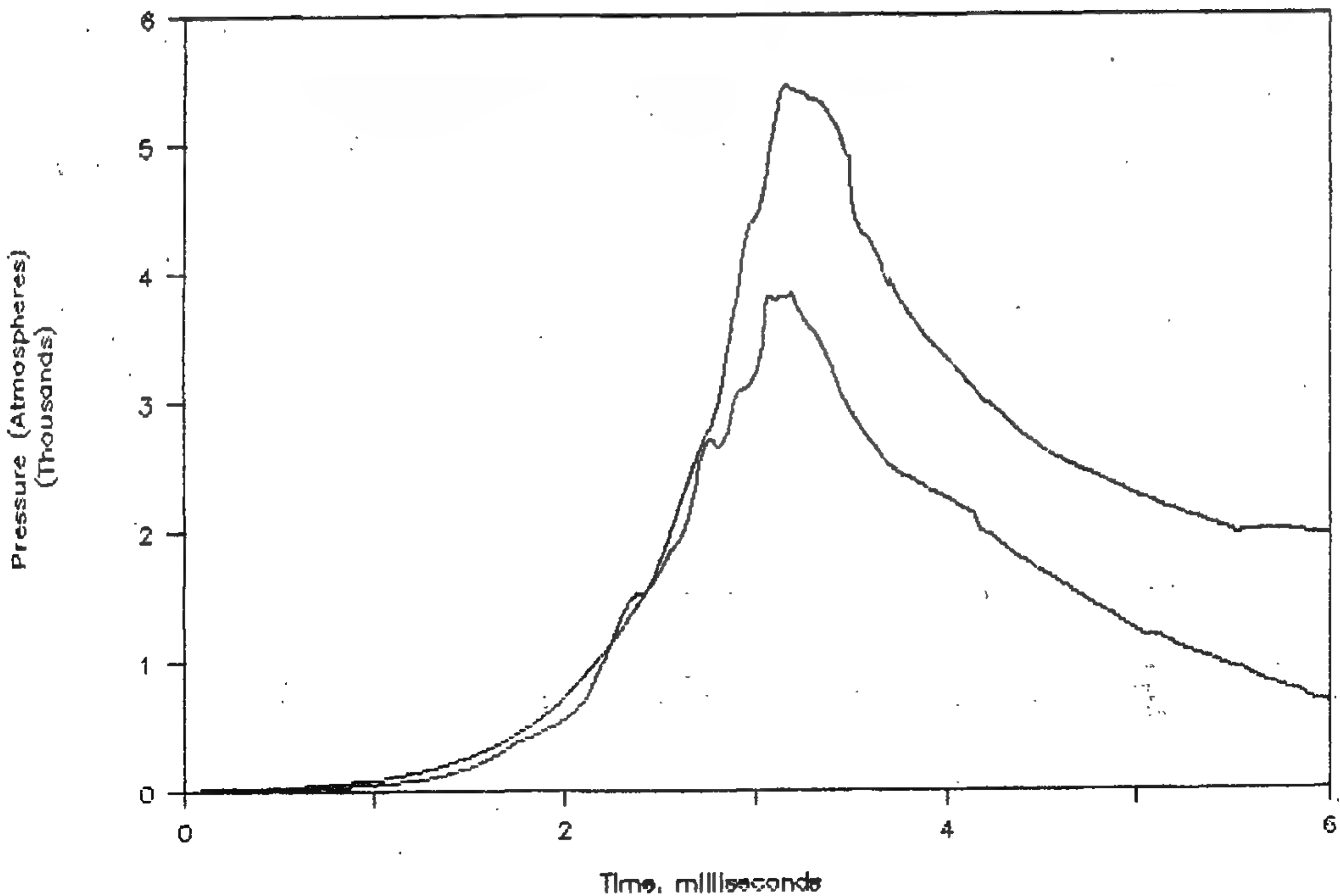


GT - Devices

GENERAL DYNAMICS
Land Systems Division

120 MM FETC SIMULATION

STUB AND PROJECTILE BASE PRESSURES

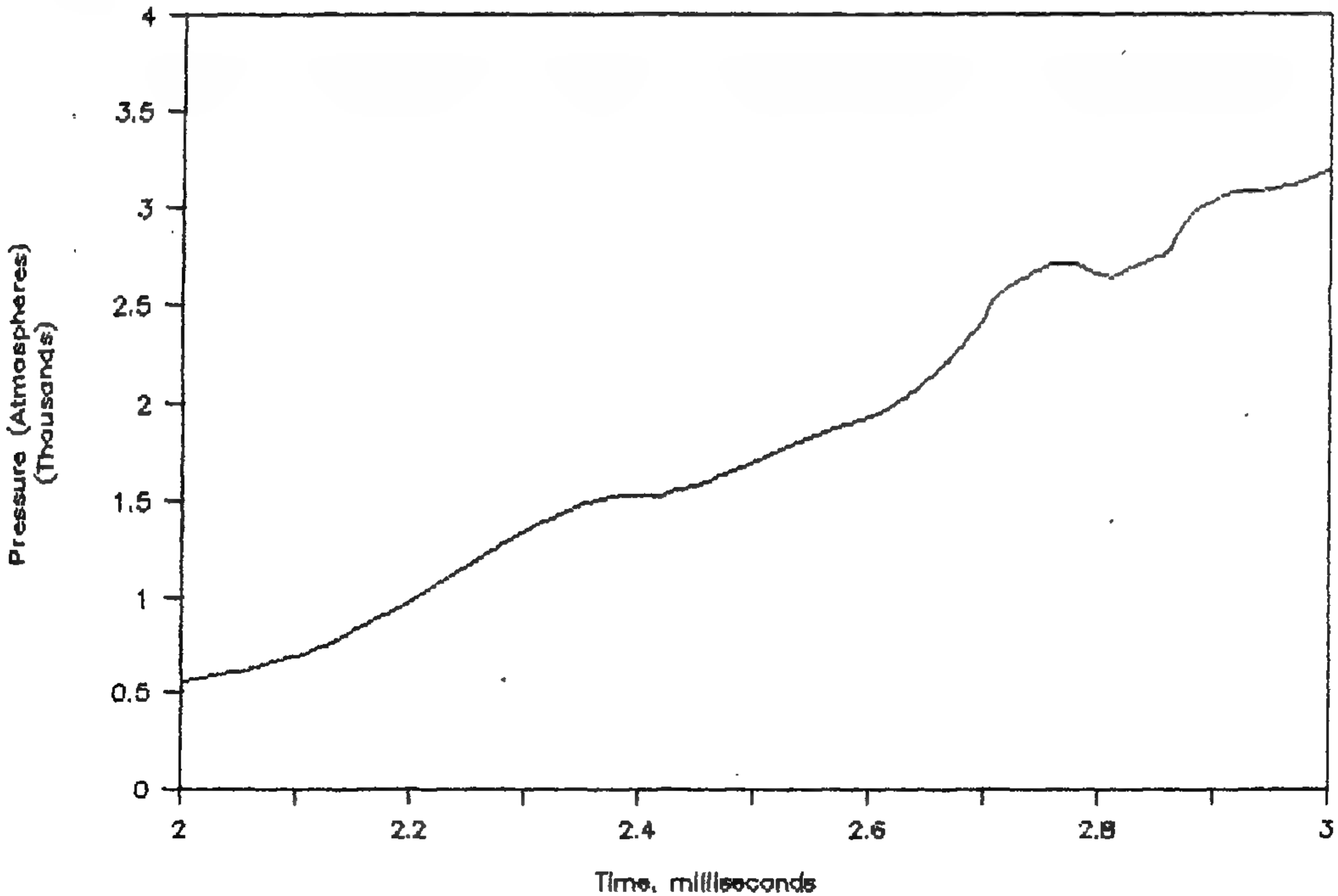


GT - Devices

GENERAL DYNAMICS
Land Systems Division

120 MM FETC SIMULATION

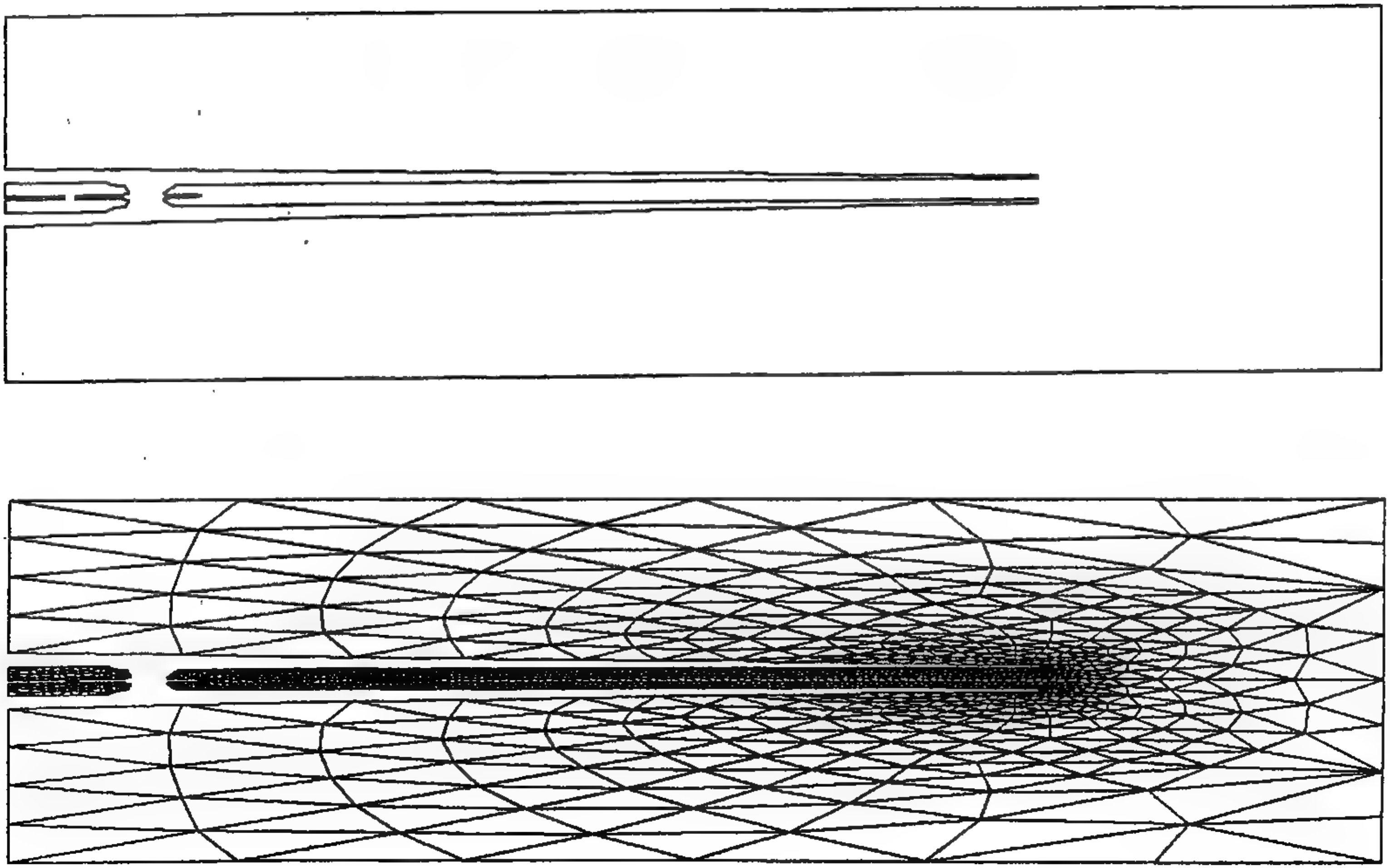
DETAIL OF PROJECTILE BASE PRESSURE



GT - Devices

GENERAL DYNAMICS
Land Systems Division

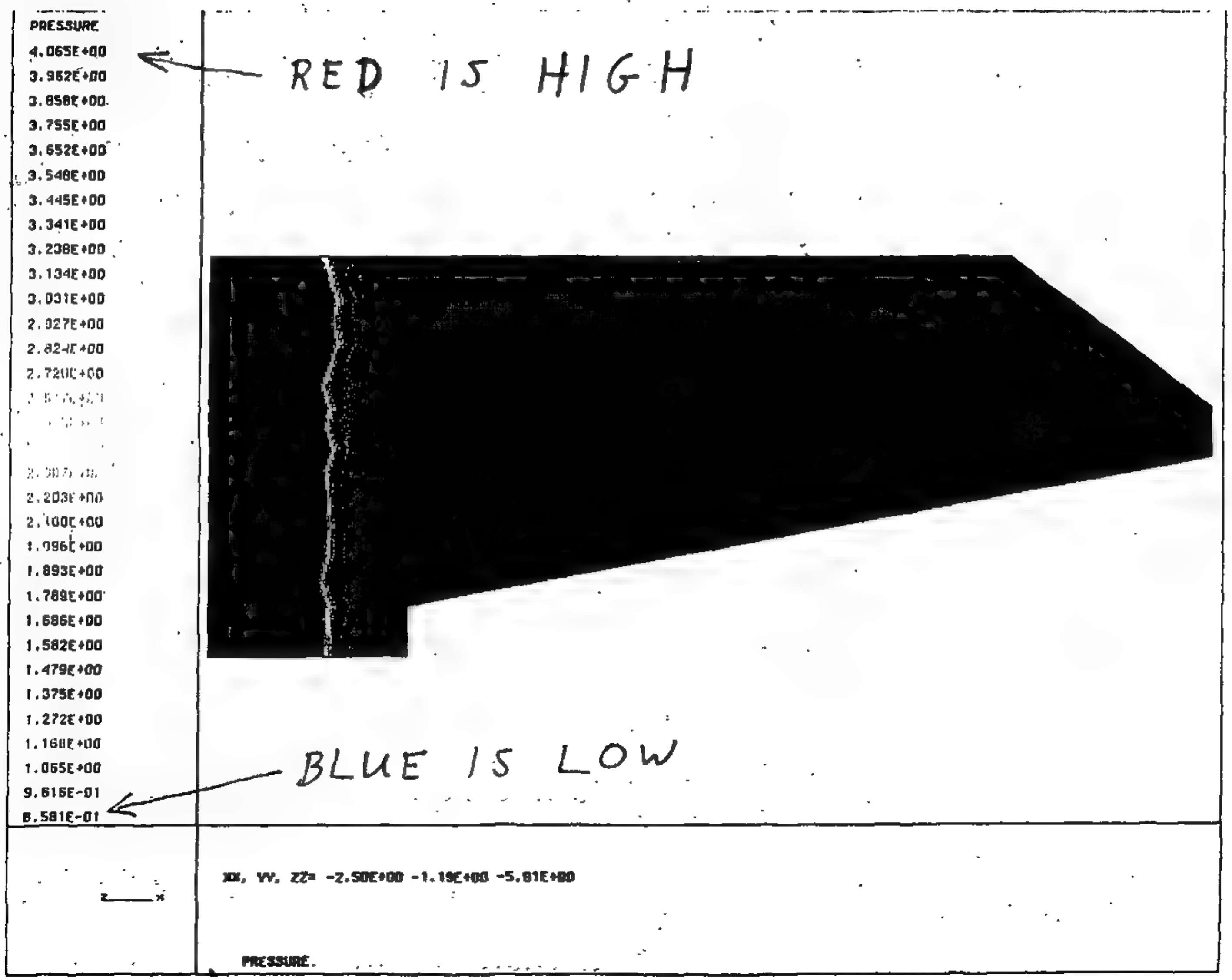
120 MM FETC GRID



GT - Devices

GENERAL DYNAMICS
Land Systems Division

COLOR PLOT LAYOUT



SUMMARY

1. WATER HAMMER: SOUND SPEED DEPENDENCE ON PRESSURE IS KEY TO DYNAMICS OF ELECTROTHERMAL AND LIQUID PROPELLANT GUNS.

2. CLOSED BOMB: AN IDEAL METHOD FOR VALIDATING BURN MODELS.

3. IBHVG2 TEST: UNSTRUCTURED FINITE-ELEMENT METHODS WORK SPECTACULARLY IN GUN GEOMETRY!

INTENTIONALLY LEFT BLANK.

SPECIAL DIAGNOSTICS AND INSTRUMENTATION

Rex D. Richardson and Michael D. Haworth
Science Applications International Corporation
Albuquerque, NM 87106

ABSTRACT

SAIC and FMC experimenters are currently planning to field two special diagnostics for application on the Defense Nuclear Agency's ETC Propulsion for Enhanced Gun System Effectiveness program. A three-frame flash x-ray radiographic system is being developed to observe dynamic mixing processes in the 30 mm FMC CAP_{tm} test fixture. Results of x-ray transmission calculations along with cold model flash x-ray tests at 300 kV will be presented. Data analysis and image processing techniques will be described. The second diagnostic is a laser rangefinder system designed to track the position of a projectile in-bore from shot start to muzzle exit at a resolution of less than one centimeter and a data rate of 40 kHz. System design issues and the prototype test plan will be discussed.

JANNAF Workshop on
ETC Modeling and Diagnostics
June 1991

Defense Nuclear Agency

SPECIAL DIAGNOSTICS AND INSTRUMENTATION*

Prepared by

Dr. Rex D. Richardson

Science Applications International Corporation
Albuquerque, New Mexico

* WORK SUPPORTED BY THE DEFENSE NUCLEAR AGENCY

FMC

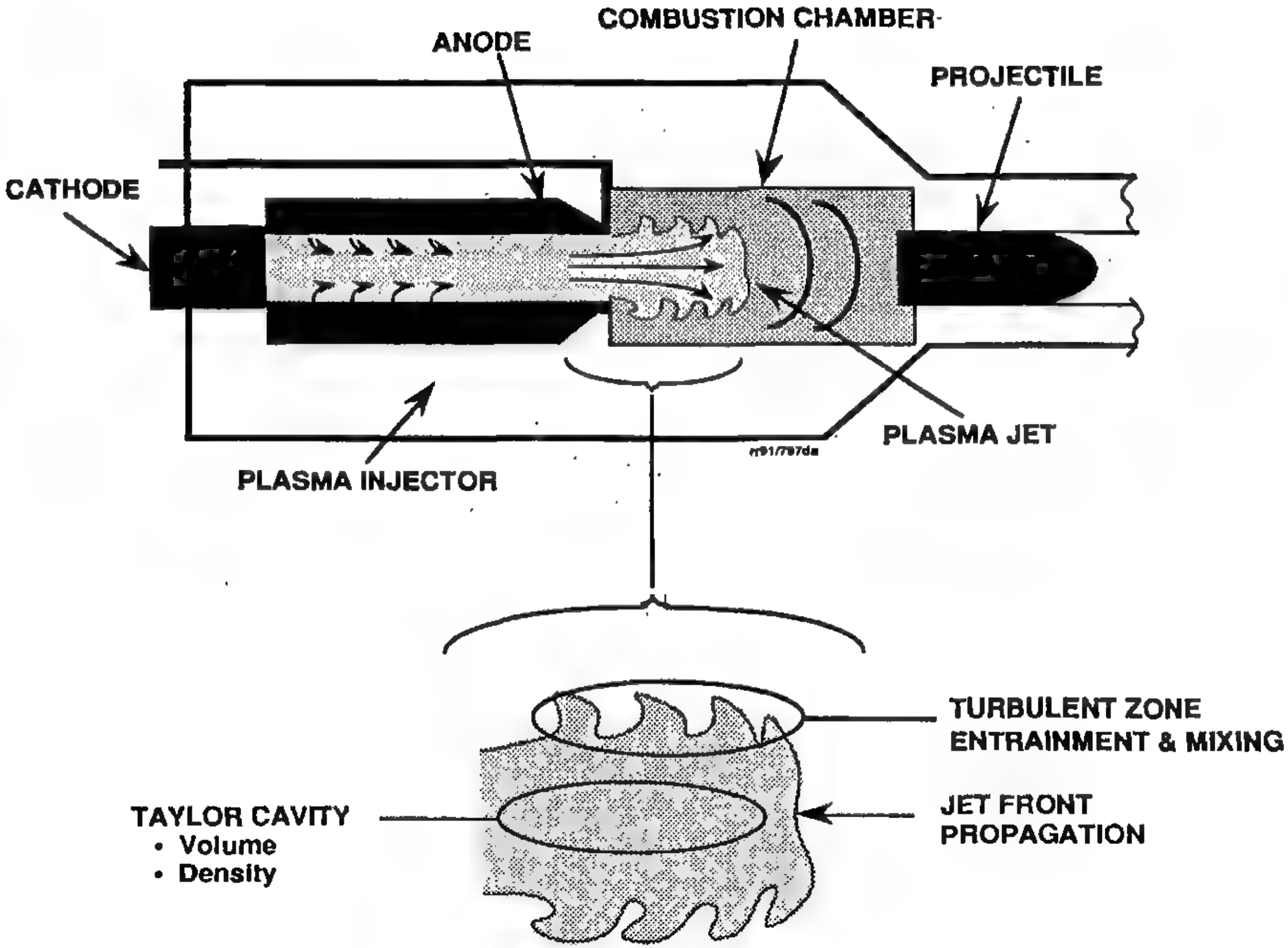
SAIC Science Applications International Corporation An Employee-Owned Company

RR 91/860 hs/da

INTRODUCTION

- X-Ray radiography of fluid/plasma jets
  - Overview
  - Technical approach
  - FSCATT runs
  - 300 kV FXR tests
  - Image analysis
- Laser rangefinder in-bore diagnostic
  - Conceptual design,system issues

FLASH X-RAY OBSERVABLES
CAP SYSTEMS



Science Applications International Corporation
An Employee-Owned Company

RR 91/797 hs/da

TECHNICAL APPROACH

ADD X-RAY WINDOW TO BURN RATE FIXTURE

DEVELOP 3-FRAME FLASH X-RAY SYSTEM

↓

OBTAIN THREE FILM RADIOGRAPHS AT SELECTED TIMES DURINGTHE 800μs CAP DISCHARGES

↓

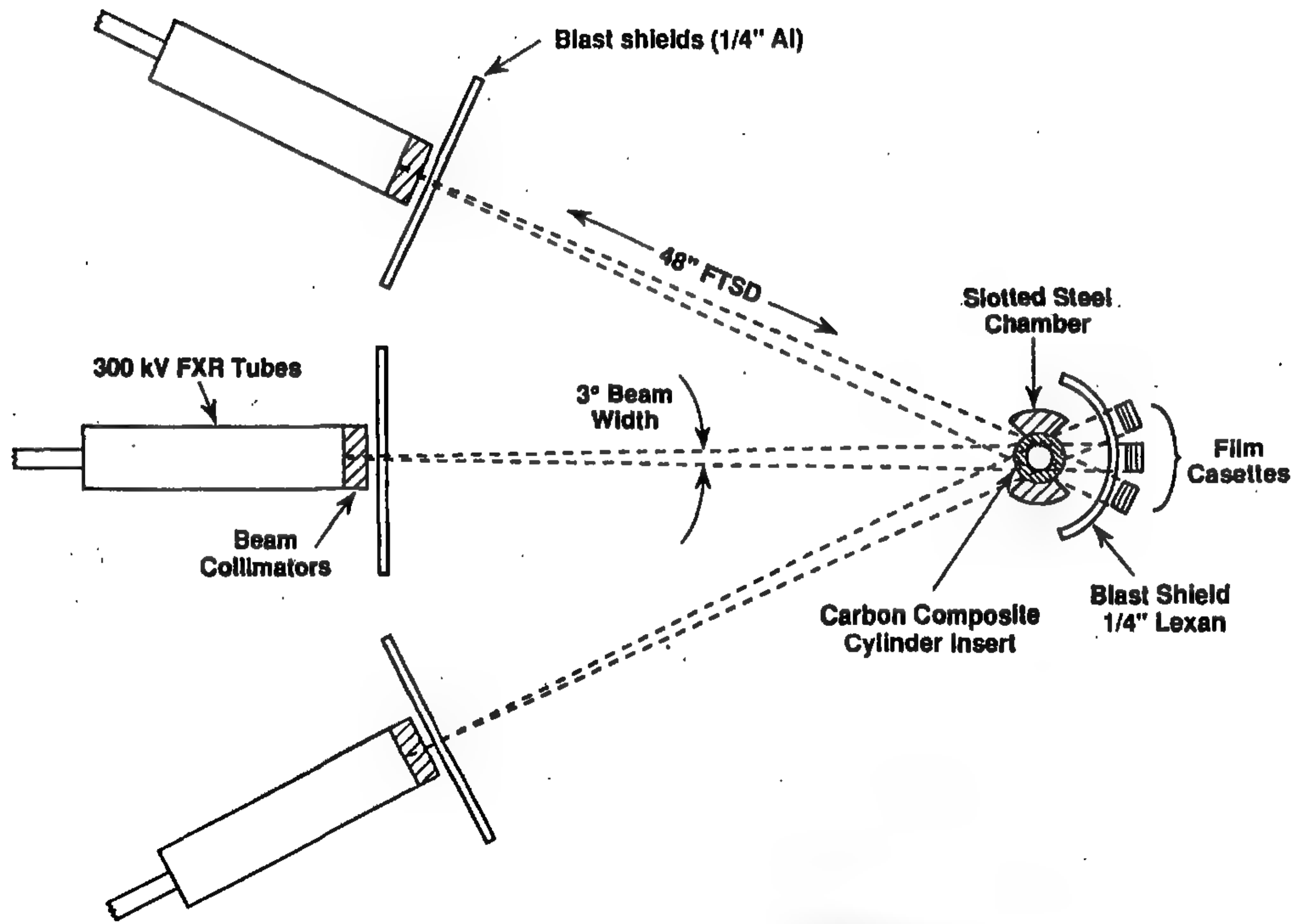
DIGITIZE FILM USING CCD VIDEO CAMERA AND FG-BOARD

↓

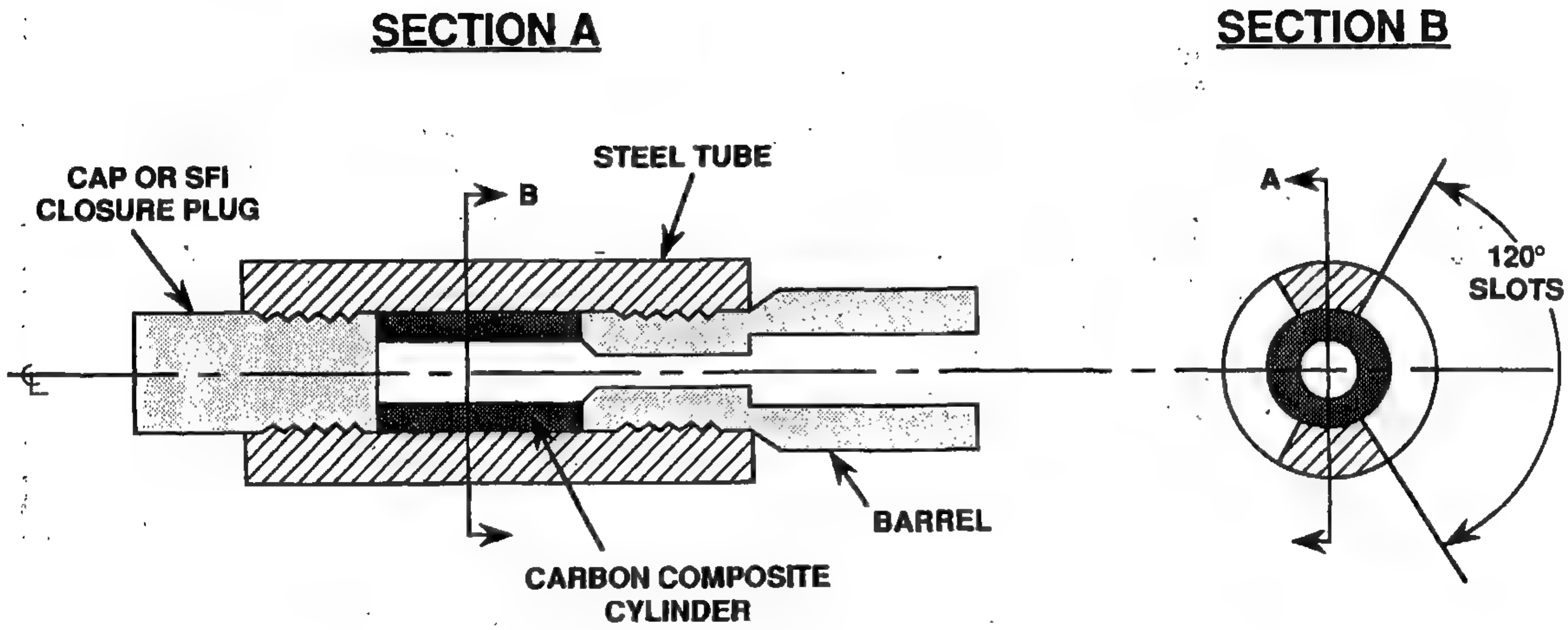
USE COMPUTER IMAGE PROCESSOR TO EXTRACT AND ENHANCE DENSITOMETRIC DATA

rr91/793da

LAYOUT OF 3 FRAME FXR SYSTEM



BURN RATE FIXTURE MODIFICATION FOR X–RAY RADIOGRAPHY



rr91/797 da

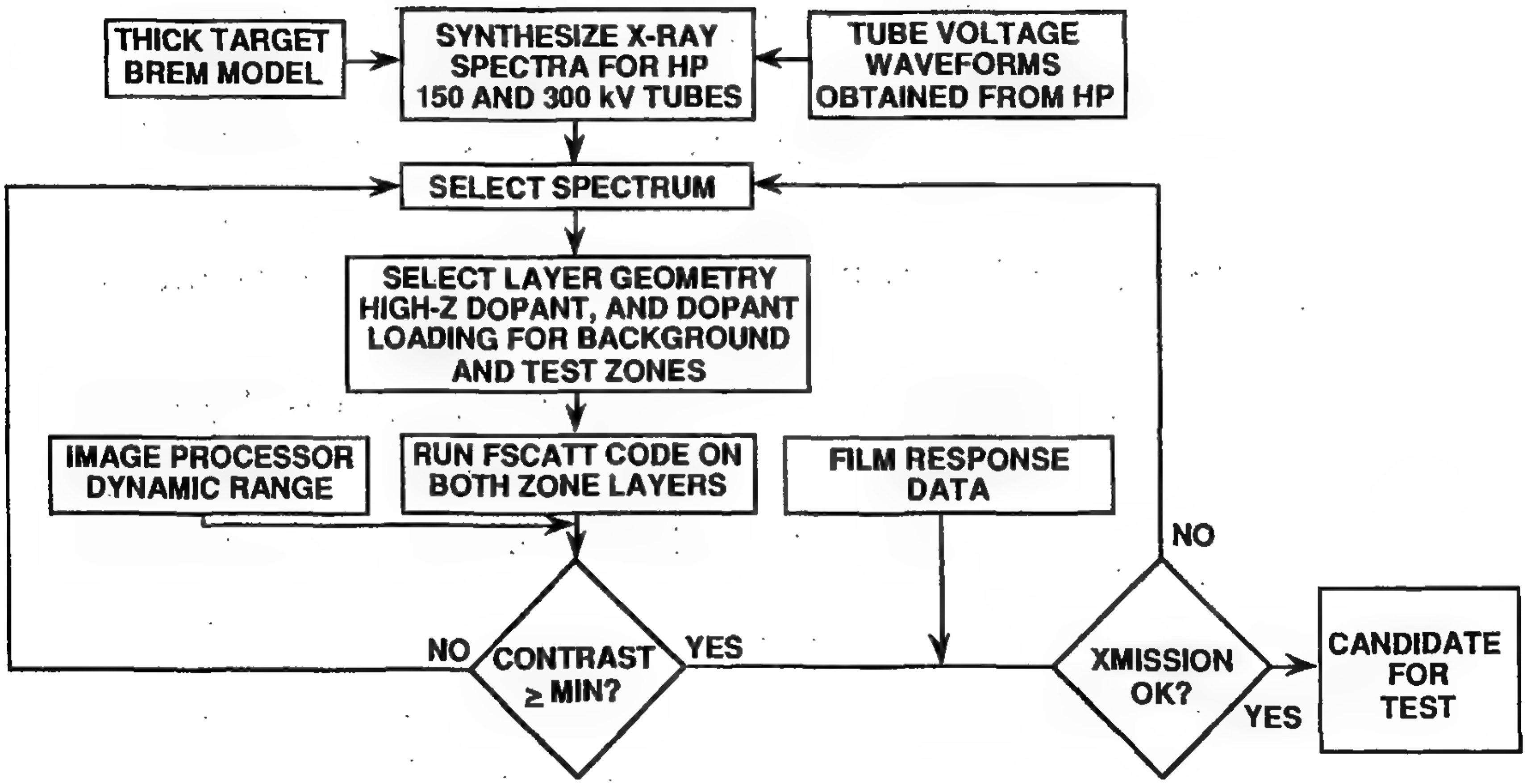
SAIC Science Applications International Corporation
An Employee-Owned Company

RR 91/797 hs/da

FSCATT CODE RUNS

- X-ray transport and energy deposition
- Discrete ordinate, ID
- PE absorption, Compton scattering and fluorescence
- Input/output energy flux and fluence
- Angular distribution of secondary radiation

X-RAY TRANSMISSION MODELING

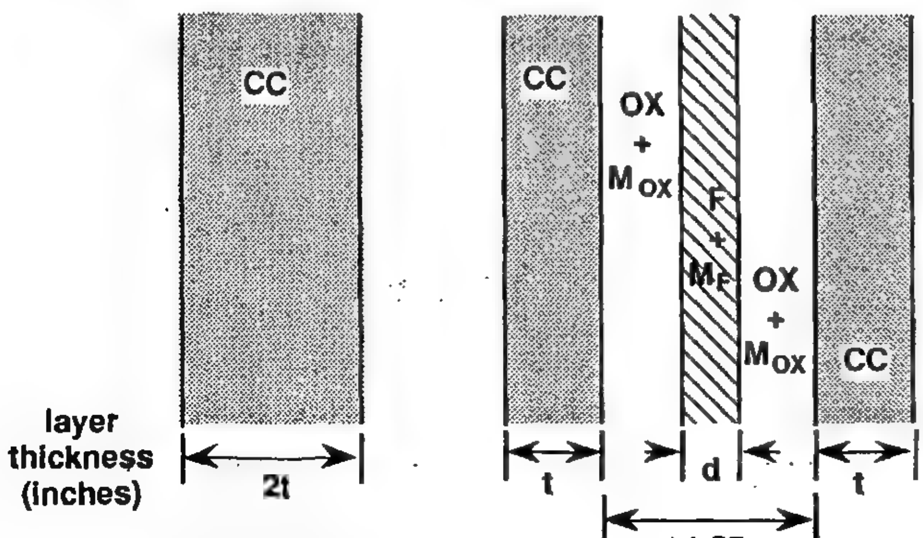


FSCATT INPUT GEOMETRIES

Abbreviations

CC	Carbon composite	W	Tungsten
OX	Oxidizer	Ba	Barium
F	Fuel	Au	Gold
M_F	Mass fraction of High Z dopant in Fuel	M_{OX}	Mass fraction of High Z dopant in Oxidizer

Case 1 **Case 2**



t = 0.5, 0.75, 1.0

For Case 2

a) d = 0, $M_{OX} = 0$

b) d = 0.2, 0.5 cm
- $M_F = 0, 0.1\ W, 0.2\ W$
  $M_{OX} = 0$
- $M_F = .07\ W + .07\ Ba + .07\ Au$
  $M_{OX} = 0$

c) d = 0.2, 0.5 cm
  $M_F = 0$ (100% & 25% density)
  $M_{OX} = 0.1\ W, 0.2\ W$

SAIC Science Applications International Corporation An Employee-Owned Company

RR 91/797 hs/da

CONCLUSIONS OF FSCATT CALCULATIONS

- FSCATT runs show 10 – 30 percent contrast is possible for a 5 mm jet doped with high–Z material, or for a 5 mm jet penetrating a doped fluid
- Total x–ray transmitted fluence is 1 – 7 percent of incident fluence depending upon doping fraction, geometry and spectrum
- Film response data indicated marginal exposure operation at 150 kV, acceptable exposure levels at 300 kV

300 kV EXPERIMENTS

- One day test series conducted at the Alliant Techsystems Proving Ground, Minneapolis
  - HP 43733A 300 kV FXR system
  - Kodak XAR film using TI-3 or NDT-9 front and back intensifying screens
  - Automatic and hand processing
- Two mock-ups used as x-ray test objects
  - Water filled graphite cylinder with tungsten carbide doped, gelled water on axis
  - Graphite cylinder filled with tungsten carbide doped, gelled water and empty glass tube on axis

Science Applications International Corporation
An Employee-Owned Company

RR 91/060 fra/da

FLASH X-RAY RADIOGRAPHY SUMMARY AND STATUS

SUMMARY:

- FSCATT x-ray photon transport calculations show good contrast in tungsten carbide doped SFI or CAP geometries
- Carbon composite cylinders with up to one inch wall thickness may be used as the x-ray transparent chamber
- 300kV FXR experiments confirm code predictions and serve as initial optimization study
- PC based image analysis system is more than adequate for the task

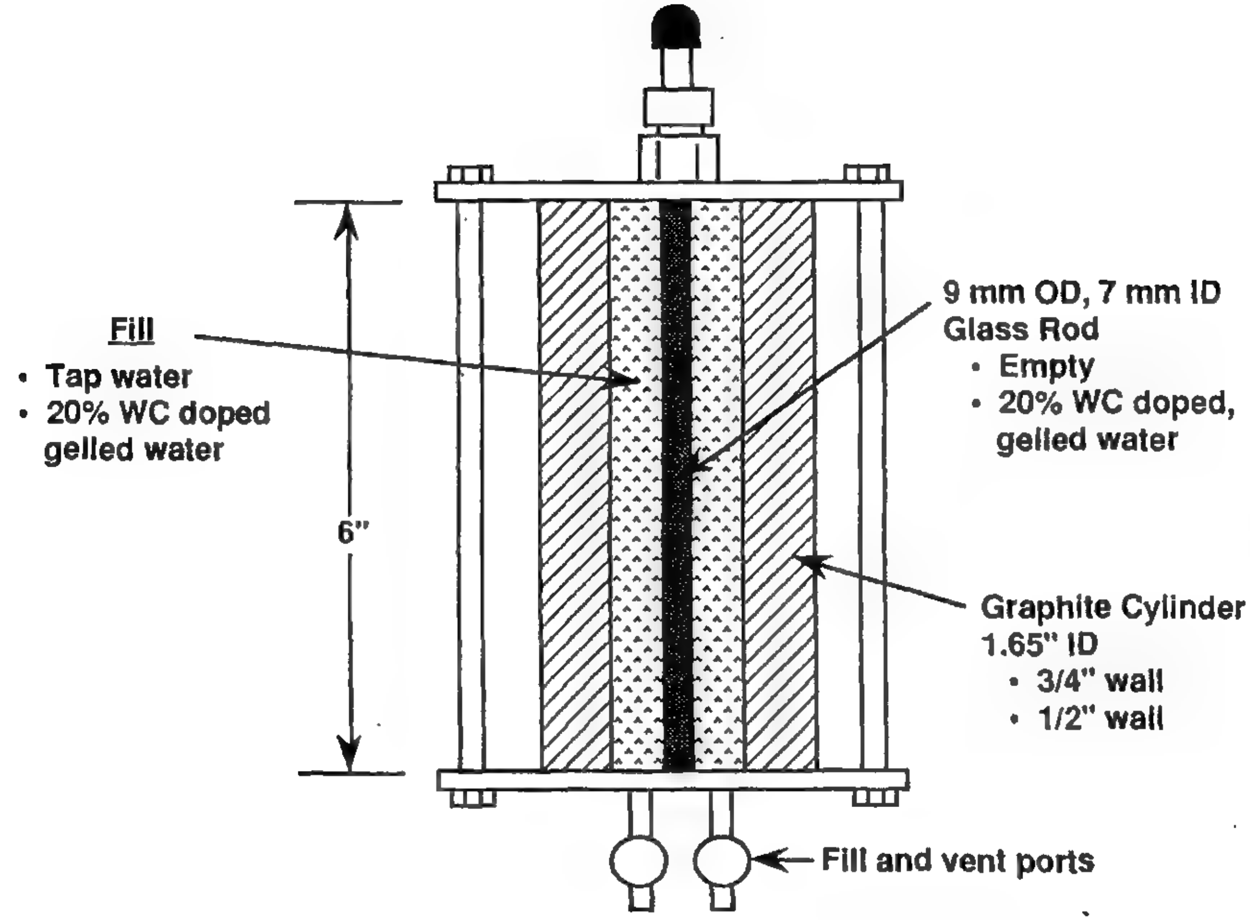
STATUS:

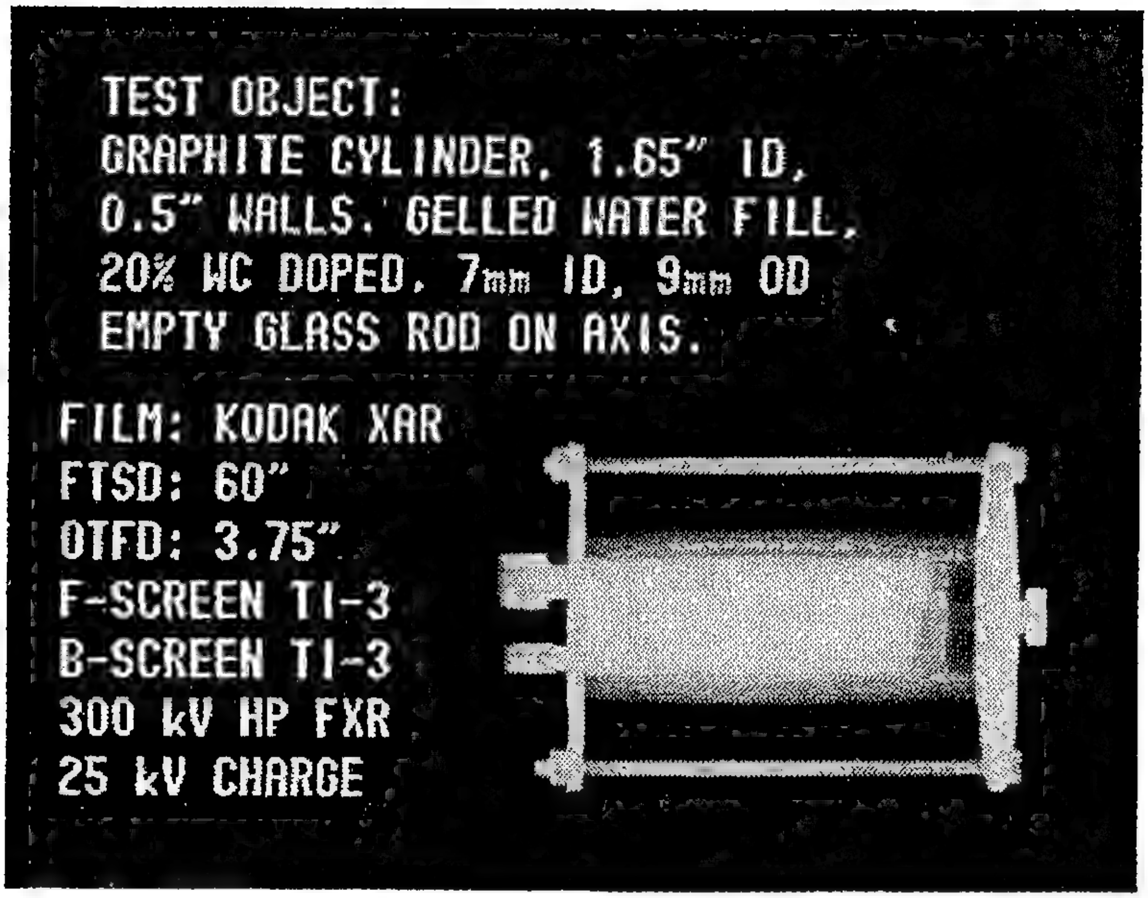
- Vendor identified for composites; FMC working on fabrication specs and prototypes
- Burn rate chamber to be ready in early July, 1991
- Alliant Techsystems will set up and operate the FXR system

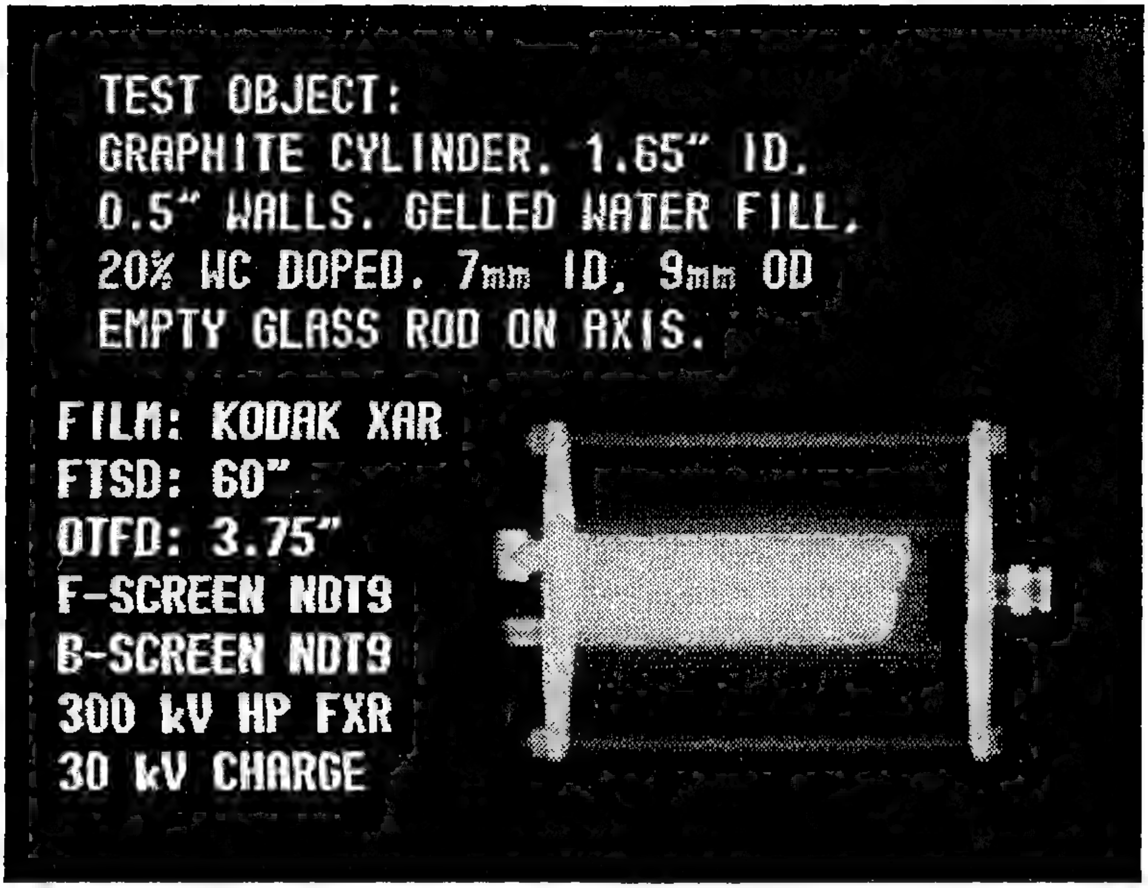
SAIC. Science Applications International Corporation
An Employee-Owned Company

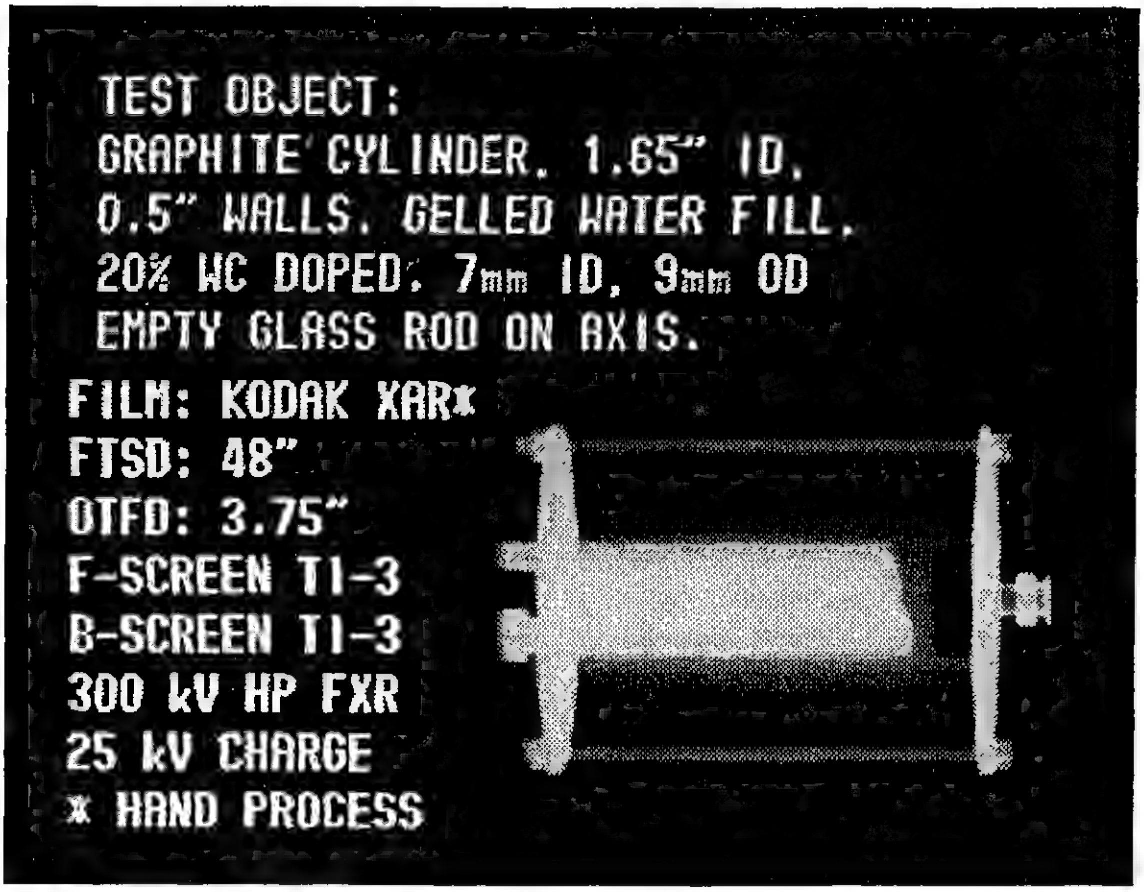
RR 91/860 hs/da

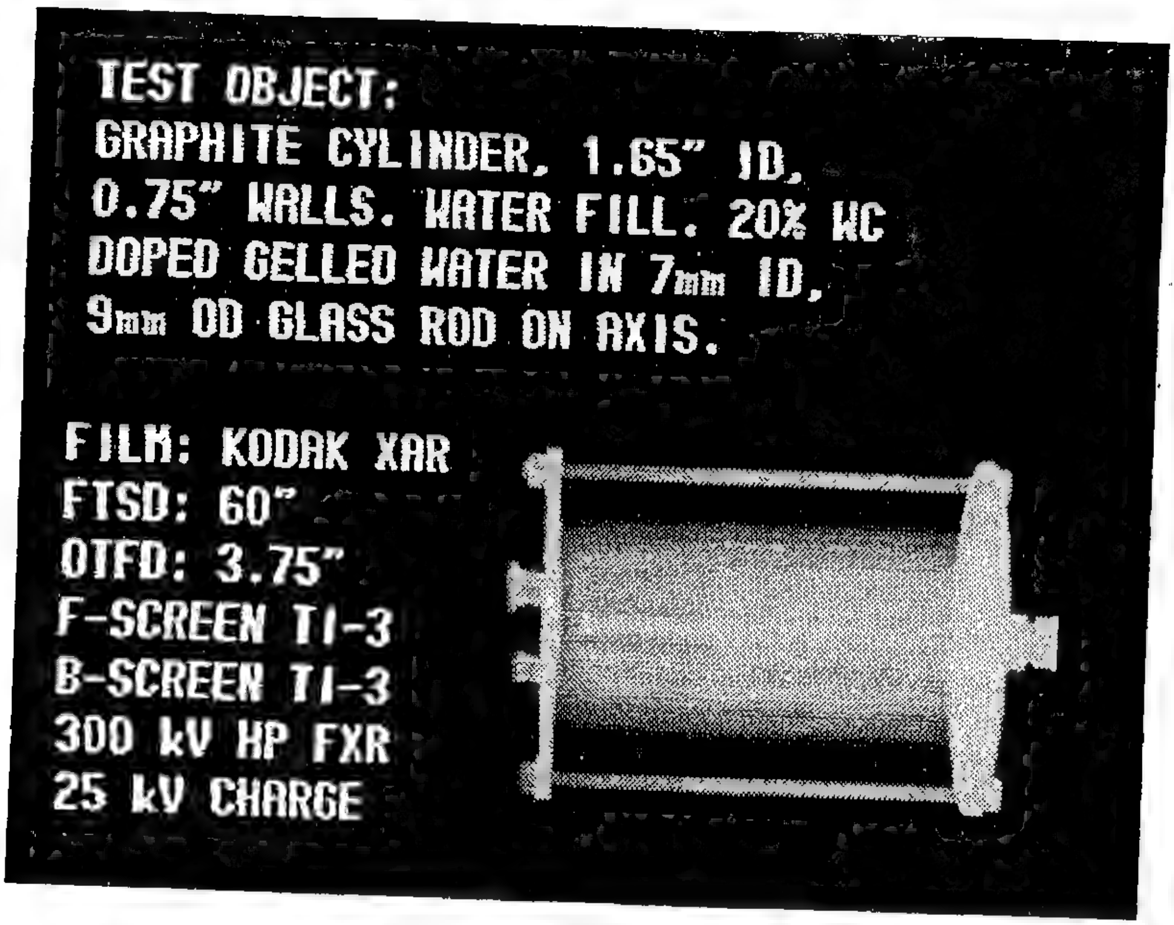
X-RAY TEST OBJECT



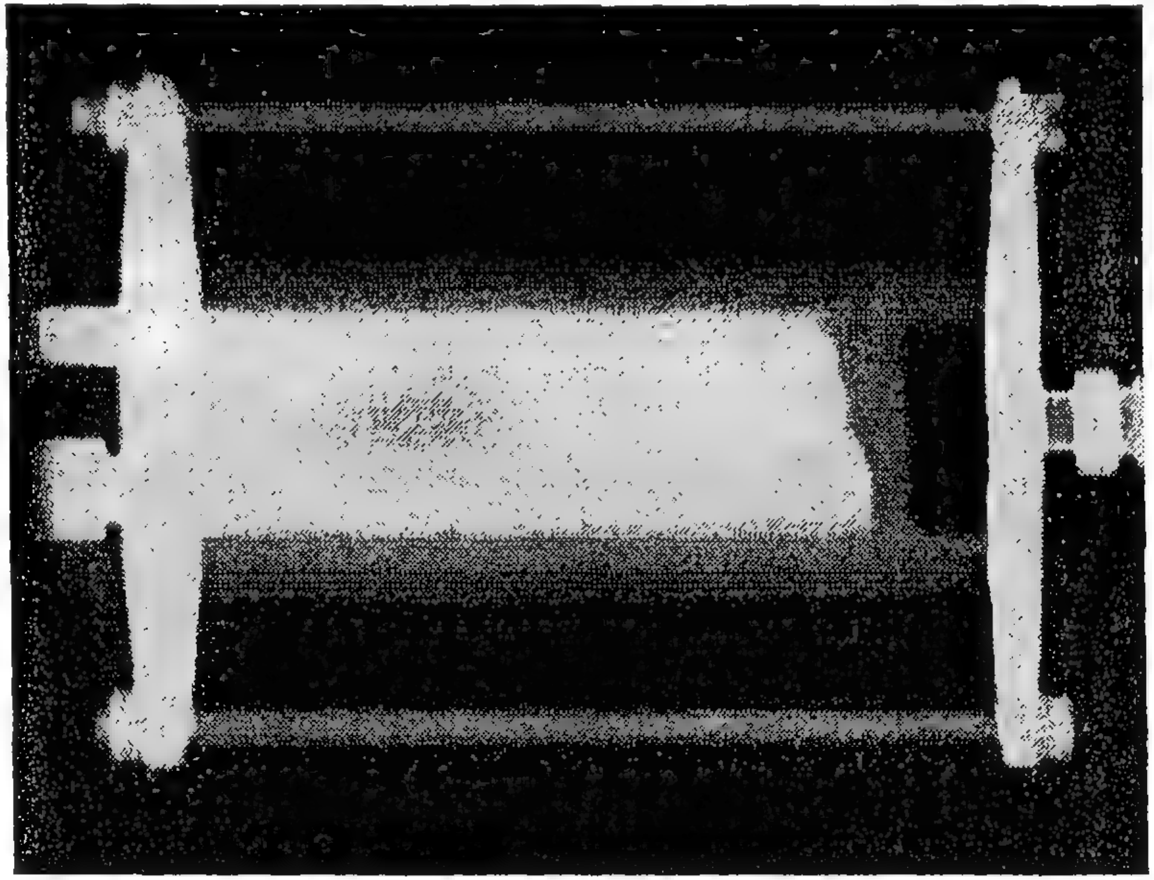

TEST OBJECT:
GRAPHITE CYLINDER, 1.65" ID,
0.5" WALLS. GELLED WATER FILL,
20% WC DOPED, 7mm ID, 9mm OD
EMPTY GLASS ROD ON AXIS.
FILM: KODAK XAR
FTSD: 60"
OTFD: 3.75"
F-SCREEN TI-3
B-SCREEN TI-3
300 kV HP FXR
25 kV CHARGE


TEST OBJECT:
GRAPHITE CYLINDER, 1.65" ID,
0.5" WALLS, GELLED WATER FILL,
20% WC DOPED, 7mm ID, 9mm OD
EMPTY GLASS ROD ON AXIS.
FILM: KODAK XAR
FTSD: 60"
OTFD: 3.75"
F-SCREEN NDT9
B-SCREEN NDT9
300 kV HP FXR
30 kV CHARGE


TEST OBJECT:
GRAPHITE CYLINDER, 1.65" ID,
0.5" WALLS, GELLED WATER FILL,
20% WC DOPED: 7mm ID, 9mm OD
EMPTY GLASS ROD ON AXIS.
FILM: KODAK XAR*
FTSD: 48"
OTFD: 3.75"
F-SCREEN T1-3
B-SCREEN T1-3
300 kV HP FXR
25 kV CHARGE
* HAND PROCESS


TEST OBJECT:
GRAPHITE CYLINDER, 1.65" ID,
0.75" WALLS. WATER FILL. 20% WC
DOPED GELLED WATER IN 7mm ID,
9mm OD GLASS ROD ON AXIS.
FILM: KODAK XAR
FTSD: 60"
OTFD: 3.75"
F-SCREEN TI-3
B-SCREEN TI-3
300 kV HP FXR
25 kV CHARGE

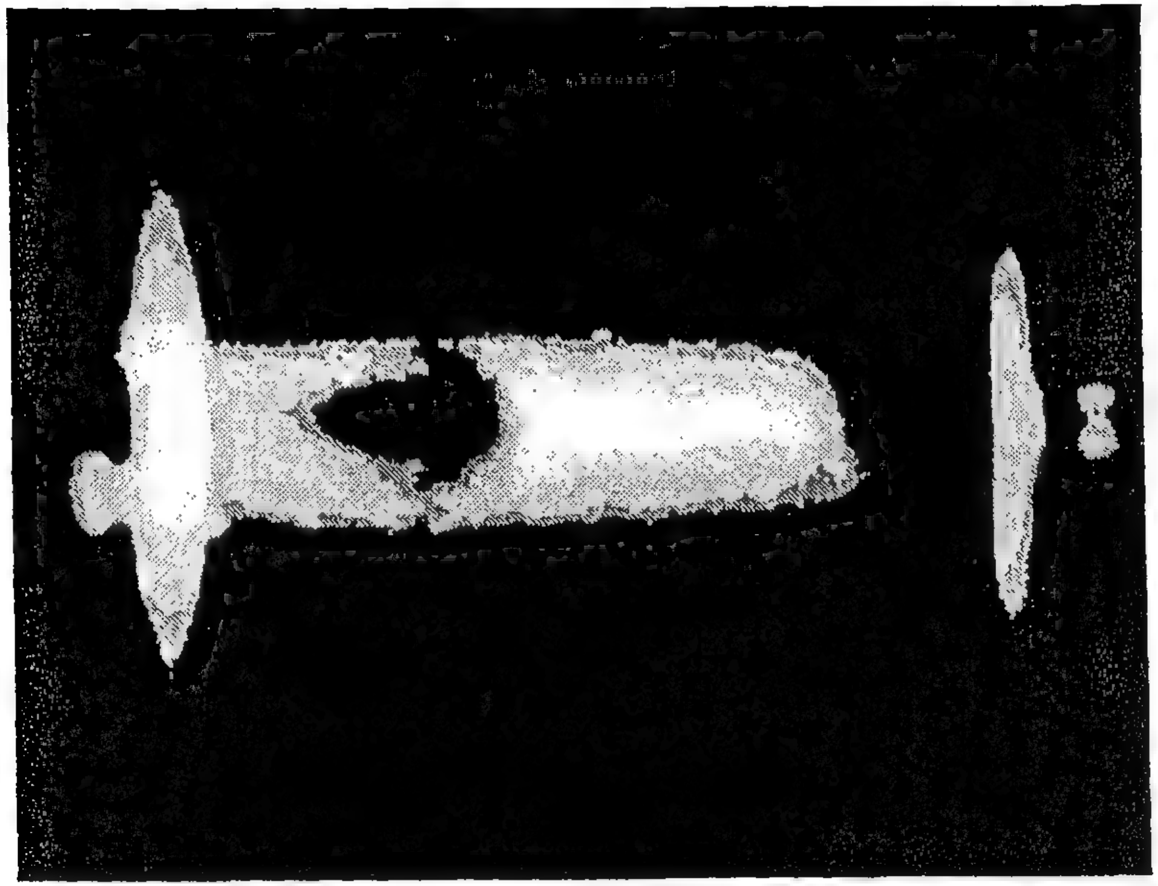
RETOUCHED RADIOGRAPH SHOWING SIMULATED "PLASMA JET"



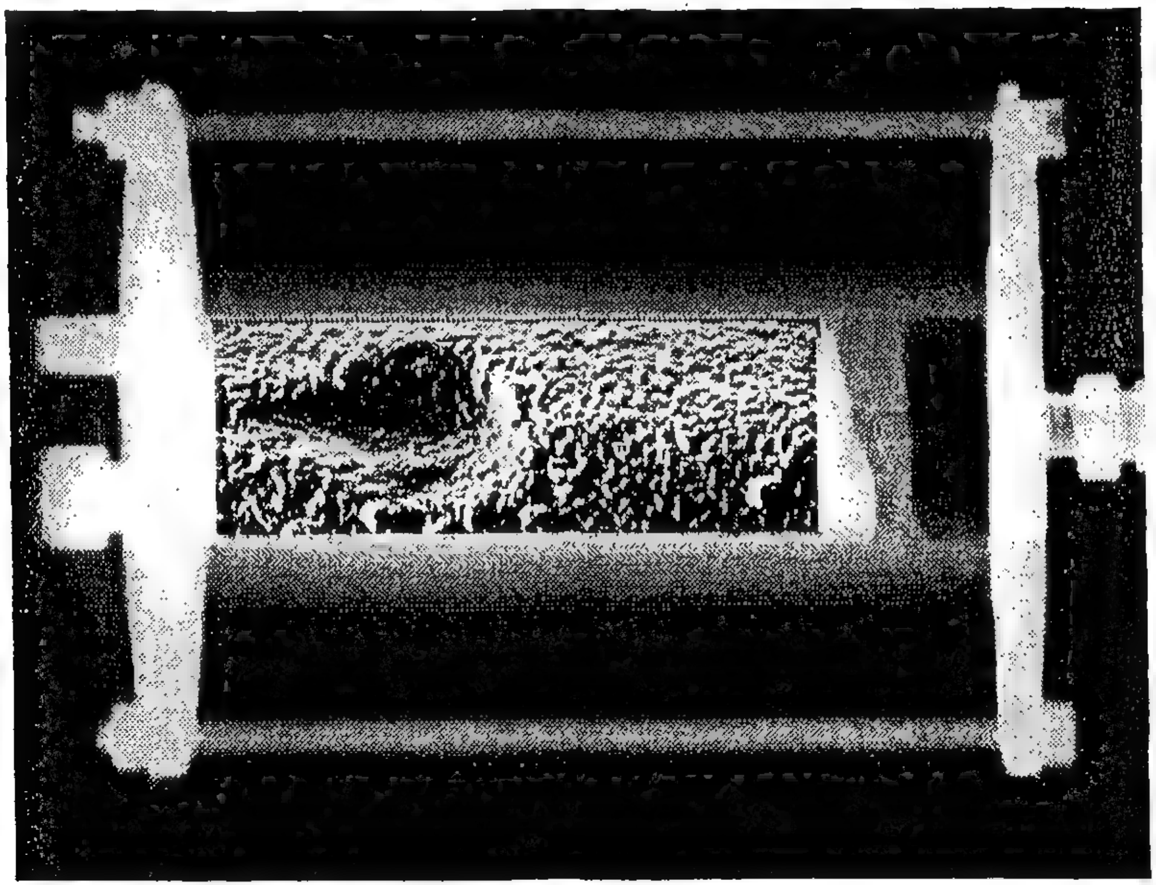
SAIC. Science Applications International Corporation
An Employee-Owned Company

RR 91/797 hs/da

EXAMPLE OF LOOK-UP TABLE OPERATOR GRADIENT ENHANCEMENT



EXAMPLE OF HORIZONTAL GRADIENT FILTER APPLICATION



LASER IN-BORE POSITION DIAGNOSTIC

GOAL: Provide precise projectile position data for comparison to interior ballistic model predictions

PROBLEM: Microwave radars are expensive and have poor resolution at low velocity. Optical Doppler velocimeters are very expensive and difficult to field in ETC gun environments

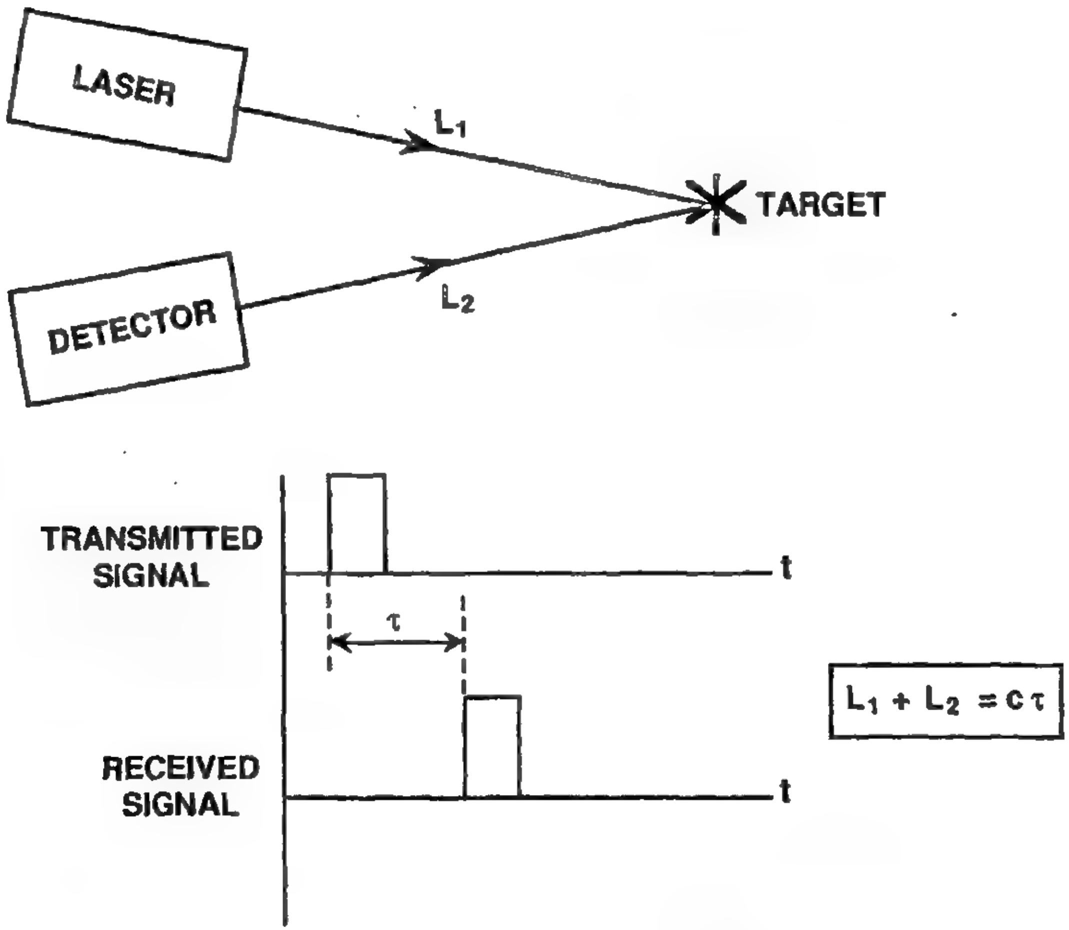
APPROACH: Use pulsed laser radar

- Inexpensive
- Robust
- Accurate; reads position at any gun velocity
- Easily calibrated <u>in situ</u>

Science Applications International Corporation
An Employee-Owned Company

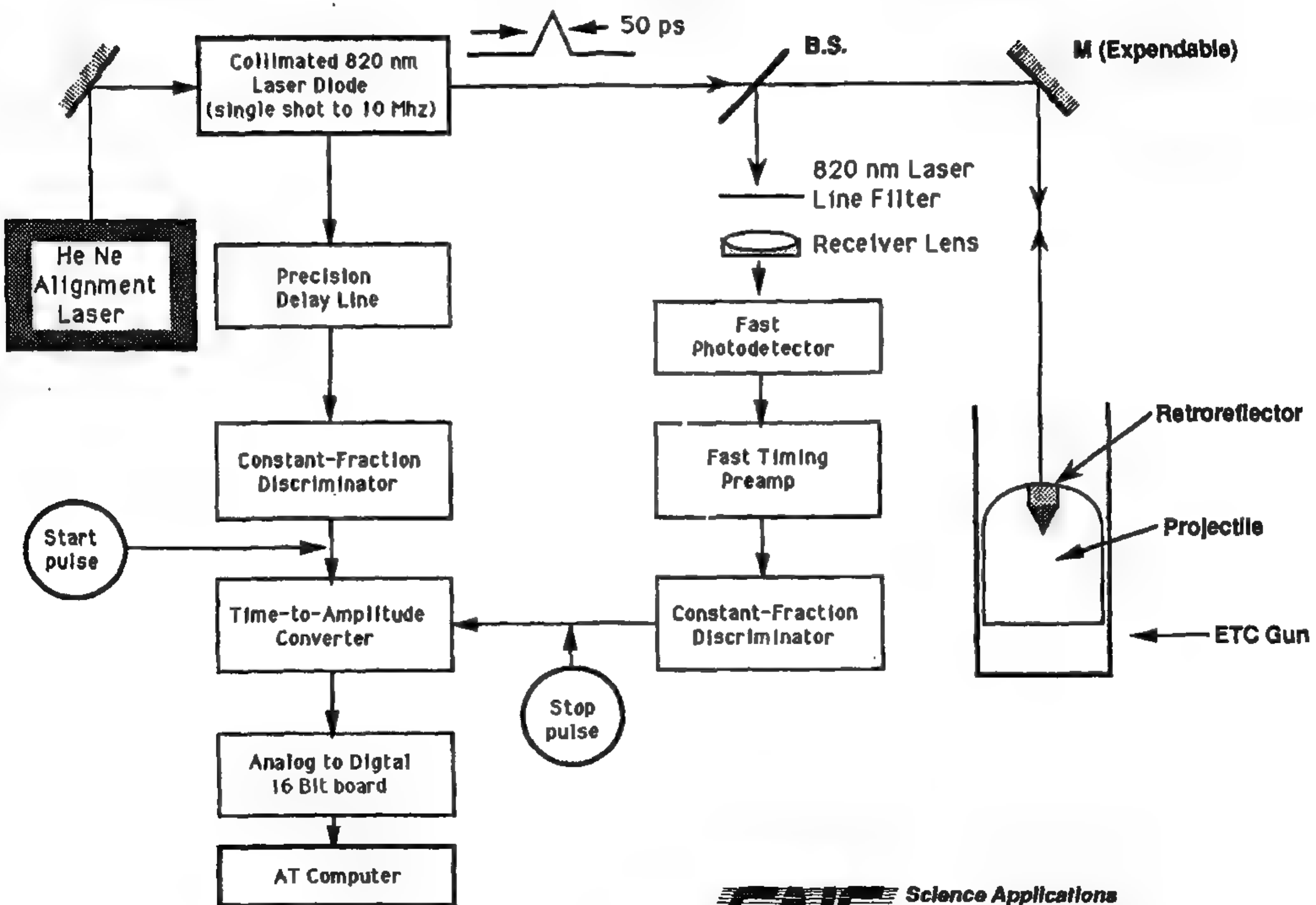
RR 91/880 ha/da

LASER RADAR OPERATING PRINCIPLE



RR 91/797 hs/da

PROJECTILE VELOCITY MEASURMENT VIA LASER RADAR



Science Applications International Corporation
An Employee-Owned Company

LASER RADAR SYSTEM PARAMETERS

Laser Wavelength	820 nm
Laser Pulse Width	50 ps
Collimated Laser Beam Divergence	0.15 mrad
Absolute Position Accuracy	2 cm
Position Jitter	$\lesssim$ 1.5 cm
Photodetector Signal Strength	1.0 V
Repetition Rate	40 kHz - 1MHz (A/D board options)

SAIC. Science Applications International Corporation
An Employee-Owned Company

RR 91/860 ha/da

LASER RADAR COMPONENT LIST

PART	MANUFACTURER	COST
150mW, 50ps, 1MHz laser diode @ 820nm with collimator	Hamamatsu	$ 8500
35ps photodetector	Opto-Electronics	3200
Vibration isolated optical bench	Newport	2700
Optical components and hardware	Newport/Melles Griot	4900
Analog timing electronics	EG&G/ORTEC	5250
1Mhz, 16 Bit, A/D DAS board	Analogic	3895
Rack mount PC system	Cyber Research	3595
DAS software (snapshot)	Cyber Research	995
		$33,035

SAIC Science Applications International Corporation
An Employee-Owned Company

RR 91/860 hs/da

LASER RADAR SYSTEMS ISSUES

OPERATION IN-BORE

- Projectile blow-by must be minimized
- Requires precision retro-reflector mounted in projectile nose
- Requires precision optical alignment for each shot

TIMING ELECTRONICS

- Millivolt resolution of time-to-amplitude converter signal is required
- Laser system and timing electronics must be electrically isolated and heavily shielded against harsh EMI environment of the ETC gun

SAIC Science Applications International Corporation
An Employee-Owned Company

RR 91/860 hs/da

INTENTIONALLY LEFT BLANK.

FIRST PRINCIPLES MODELING OF A DNA 60mm ETC GUN DESIGN

CC. Hsiao, G. T. Phillips, and F.Y. Su
Science Applications International Corporation
San Diego, CA 92121

ABSTRACT

The SAIC proprietary model BISON is a first principles CFD code which has recently been applied to the study of the interior ballistics phenomenology associated with a class of ETC gun designs. The BISON model solves the NS equations for an electrically conductive fluid but neglects magnetic forces. BISON treats multiple phases, turbulence, multi-species, and chemistry making it well suited for the study of interior ballistics.

BISON treats the advocation terms in the conservation equations using a fourth order in space, second order in time FCT algorithm. Adaptive gridding is included for accuracy and economy and makes use of both continuous and discrete second order rezoning algorithms. A non-equilibrium multi-phase treatment is available in BISON through a discrete, stochastic particle model which follows Lagrangian computational particles which are fully coupled to the continuum flow. In addition, the multi-species capability in BISON allows the treatment of equilibrium two-phase flow. Multiple fluid species are treated through separate continuum continuity equations for each species. Real equations of state for each species are provided through a unique non-iterative multi-species pressure and temperature solver. Turbulence is treated via a two-equation (k-w) model which has been validated for a variety of free and boundary layer shear flows. Reactions within the flow are computed using an eddy-breakup model which we validated under a previous DOE IC engine program. This model assumes that the chemical kinetic rates are fast compared with the turbulent mixing rates so that flame propagation is mixing controlled.

This presentation will demonstrate the effectiveness of the BISON model in modeling complex interior ballistics processes. A test case will be shown which describes the interior ballistics of a 60 mm ETC gun fixture which is being used in the DNA ETC Gun Program. Comparison of pressure transducer data with model predictions clearly shows that the computational approach is capable of capturing the detailed structure present in the experimental data.

First Principles Modeling of a DNA 60mm ETC Gun Design

by

CC Hsiao

Gary Phillips & Fred Su

Science Applications International Corporation

July 9-11, 1991

presented at

JANNAF Workshop ETC Modeling & Diagnostics

Aberdeen Proving Ground, MD

July 9, 1991

FMC

BISON Model

SAIC
An Employee Owned Company

High Order Numerics

- 4th Order in Space, 2nd Order in Time FCT Scheme
- High Order Adaptive Gridding
- Arbitrary Problem Geometry Specification

First Principle Physical Models

- Plasma Model
- Multi-Phase Continuum Model
- Multi-Phase Discrete Particle Model
- Chemical Reactive Flow Model
- Turbulence Model
- Real Equations-of-State

Governing Equations

- Species Transport Equations
- Navier-Stokes Equations
- Turbulence Equations

July 9, 1991

FMC

Plasma Model

SAIC An Employee Owned Company

Physics Approximations

Multi-level multi-species Saha code for ionization

High Beta plasma

Hydrodynamic time scales >> Plasma Times

Solve for Potential

Derive Electric Field

Add Heat to Fluid

Can be coupled to PFN

Specify equipotential surfaces or current density

Flexible Boundary Conditions

Real EOS table

Conductivity table

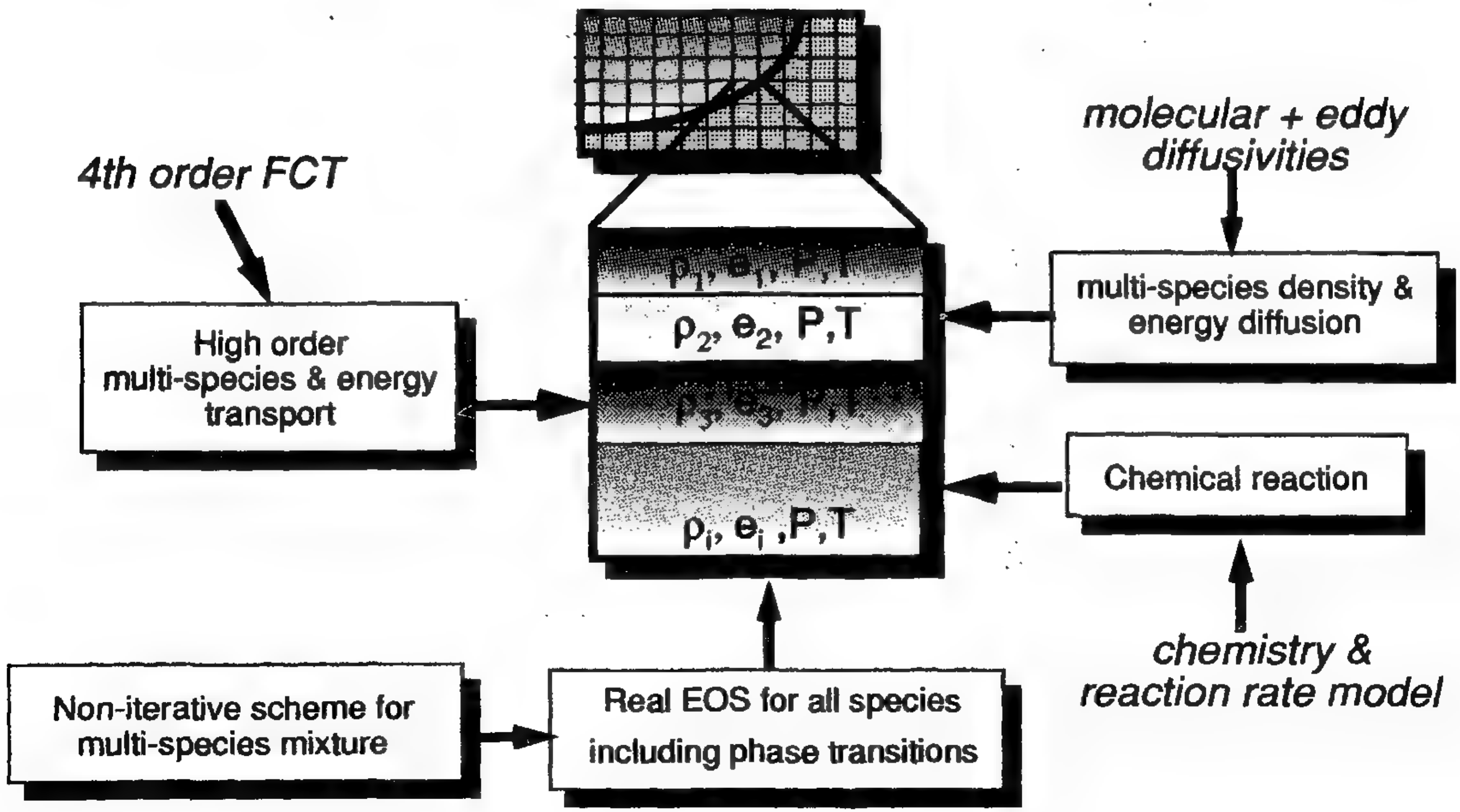
Table Driven Material Properties

July 9, 1991

FMC Multi-Phase Continuum Model SAIC

An Employee Owned Company

Assumption: Time scale to reach thermodynamic equilibrium is smaller than computational time step



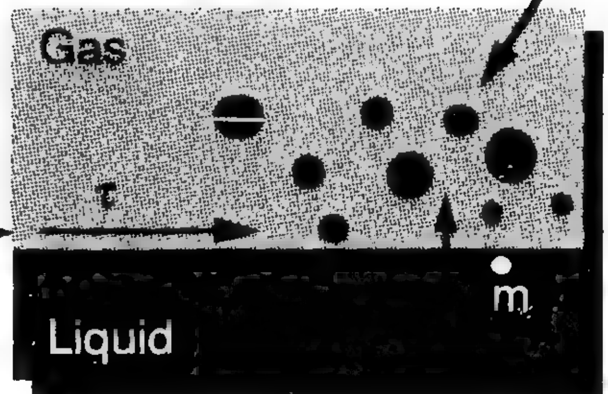
Multi-Phase Particle Model

Stochastic droplet size distribution

$$N_k / \sum_{1}^{k} N_k = \int_{D_k}^{D_{k+1}} f(D)\, d(D)$$

Non-equilibrium two-phase interactions:

mass, momentum & energy transfer through drag, heat transfer & droplet evaporation/combustion



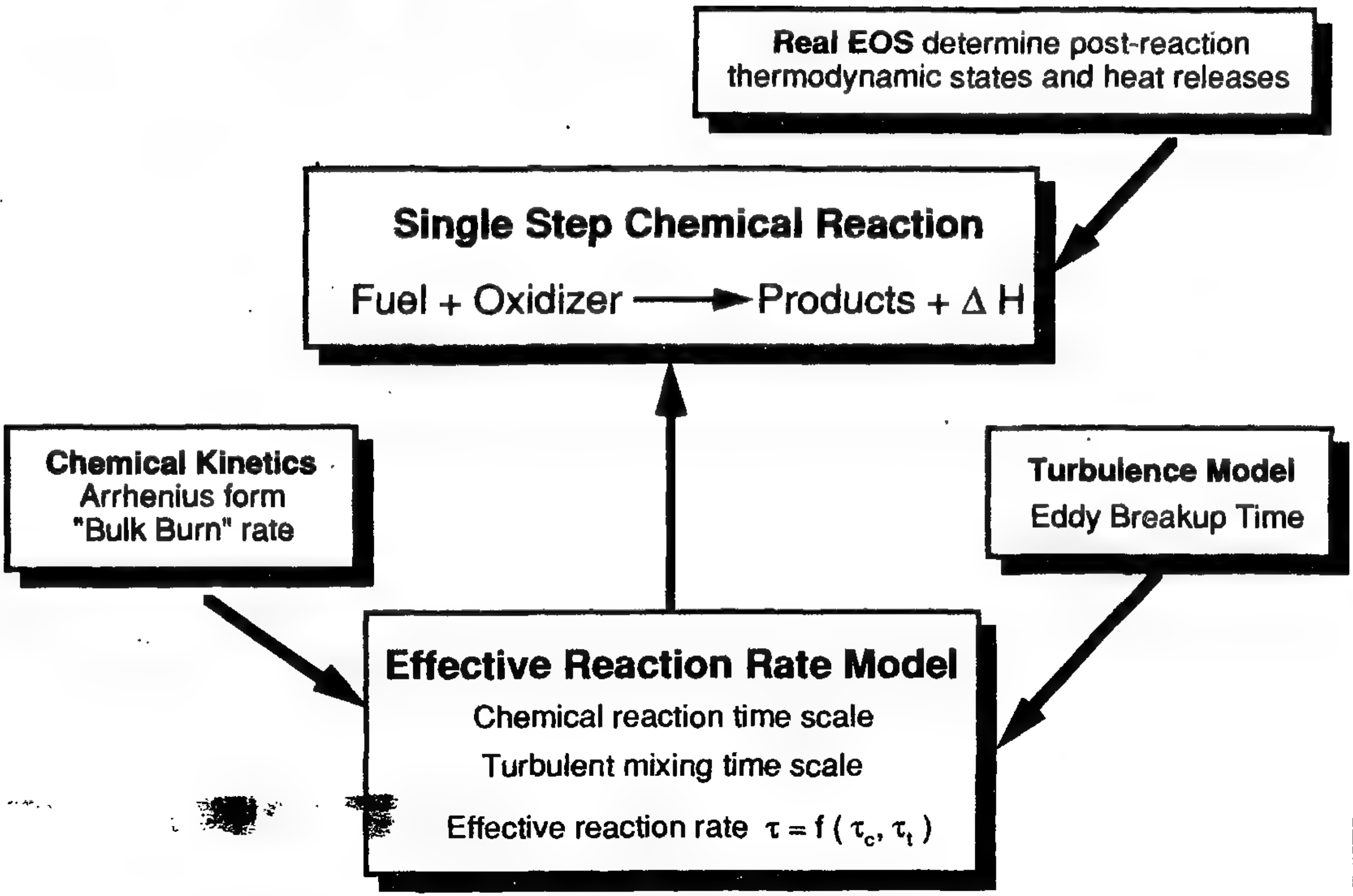
Stochastic droplet generation

$$\dot{m} = F(\tau)$$

July 9, 1991

FMC Chemical Reactive Flow Model SAIC

An Employee Owned Company



July 9, 1991

FMC

Turbulence Model

SAIC
An Employee Owned Company

Turbulent Energy & Dissipation Rate Equations

Advection **Production** **Dissipation** **Diffusion**

$$\frac{\partial(\rho\kappa)}{\partial t}+\frac{\partial(\rho u_j\kappa)}{\partial x_j}=\left\{\alpha^*\rho\bar{S}-\beta^* w\right\}\kappa-\xi^*\rho\kappa\frac{\partial u_k}{\partial x_k}+\frac{\partial}{\partial x_j}\left[(\mu+\sigma^*\rho\varepsilon)\frac{\partial\kappa}{\partial x_j}\right]$$

$$\frac{\partial(\rho w^2)}{\partial t}+\frac{\partial(\rho u_j w^2)}{\partial x_j}=\left\{\alpha\rho\bar{S}-\left[\beta+2\sigma\left(\frac{\partial l}{\partial x_j}\right)^2\right]w\right\}w^2+\frac{\partial}{\partial x_j}\left[(\mu+\sigma\rho\varepsilon)\frac{\partial w^2}{\partial x_j}\right]$$

Law of the Wall

Eddy Diffusivity
Reynolds' Stress Tensor
Turbulent heat flux vectors
Turbulent species flux vectors
Mixing time scale for reaction rate model
Fluctuating vel. for 2-phase particle model

July 9, 1991

FMC

Real Equations-of-State

SAIC An Employee Owned Company

Utilizing existing EOS Packages

DNA EOS Library
Analytical EOS
Equilibrium Chemical Codes
Bureau of Standard EOS data

Verified with available experimental data

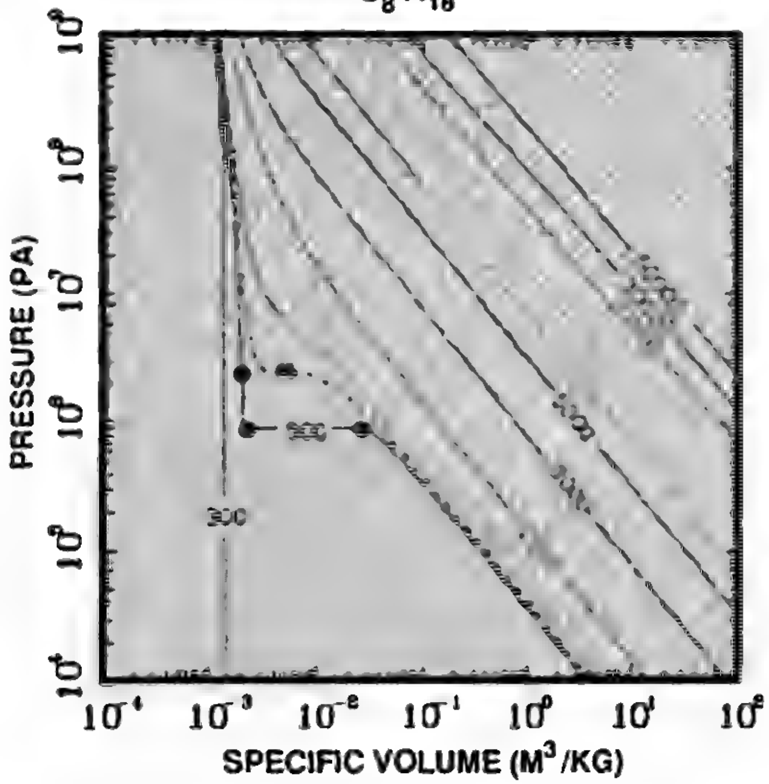
Range of Validity covers all possible ETC Gun conditions

High density, high pressure liquid state
Liquid-gas phase transition
Supercritical state
High energy plasma state

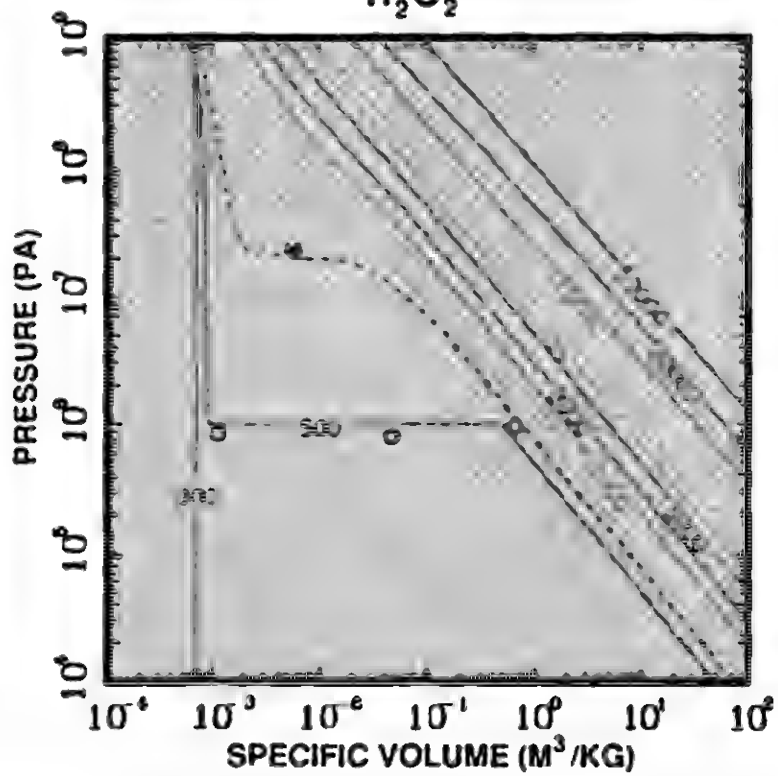
Efficient and easy-to-use table lookup format

FMC Developed Composite Real EOS

C_8H_{18}



H_2O_2



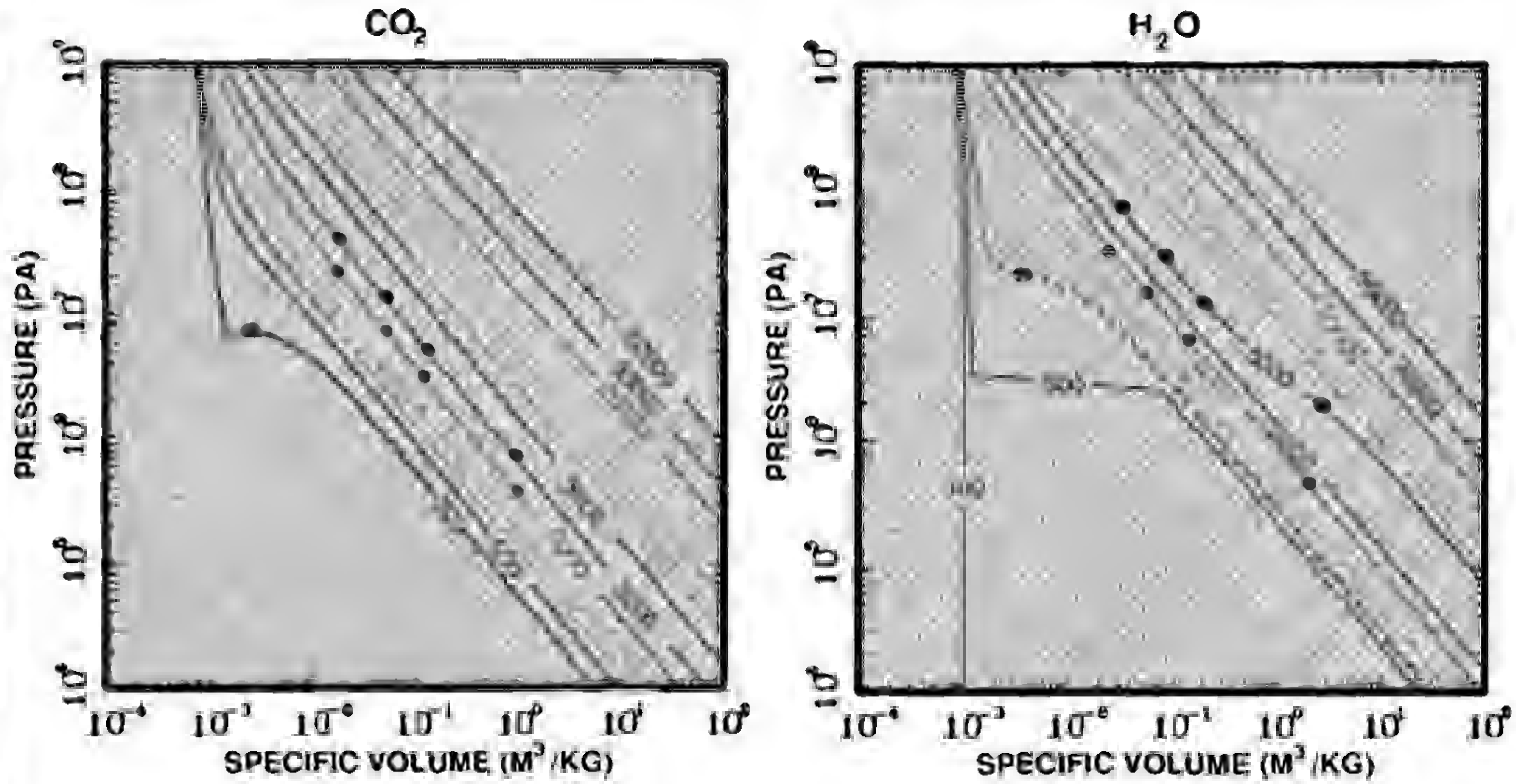
● - Data from Thermopyhsical Properties of Matter, Purdue University, 1982

✱ - Critical point, from Handbook of Chemistry and Physics, 66th Ed. 1986

□ - Data from Hydrogen Peroxide Physical Properties, FMC, 1969

✱ - Critical point, Hydrogen Peroxide Physical Properties, FMC, 1969

FMC Developed Composite Real EOS SAIC



• - data calculated from NASA-CET89 code

✲ - Critical point, from Handbook of Chemistry and Physics, 66th Ed. 1986

• - data calculated from NASA-CET89 code

✲ - Critical point, from Handbook of Chemistry and Physics, 66th Ed. 1986

June 25, 1991

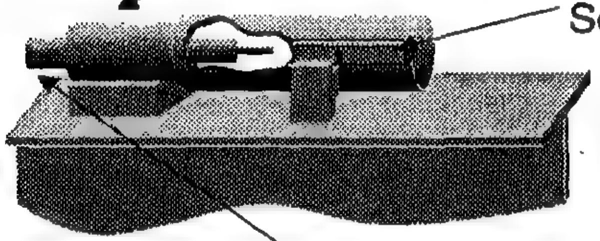
FMC

Phenomenology Experiments

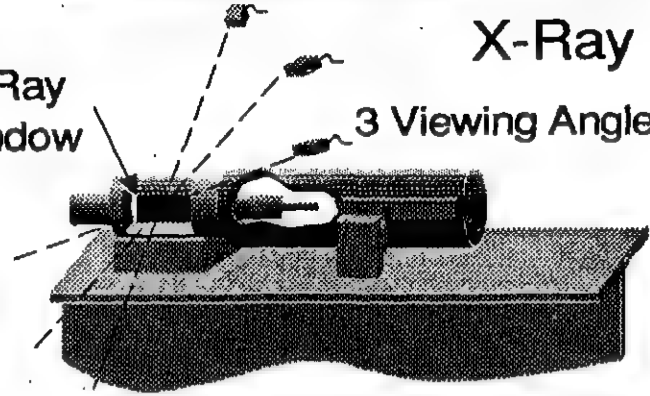
Burn Rate Tests

SAIC
An Employee Owned Company

Burn Rate



X-Ray



- Gain an understanding of plasma/fluid interactions
- Allow computation of gas generation rates
- Provide data input for model verification

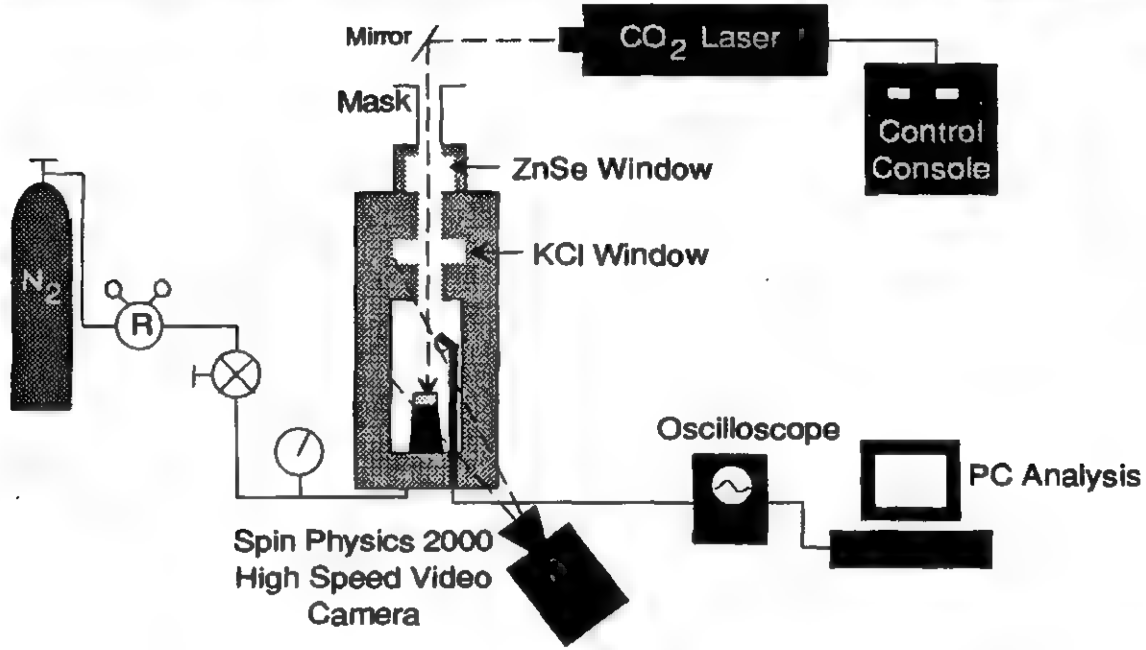
June 25, 1991

Phenomenology Experiments

Laser Pyrolysis Ignition Tests

FMC

SAIC
An Employee Owned Company



- Provide fuel-oxidizer chemical kinetic data
- Provide ignition delay time and temperature at high P
- Provide data for chemical reaction computer sub-model

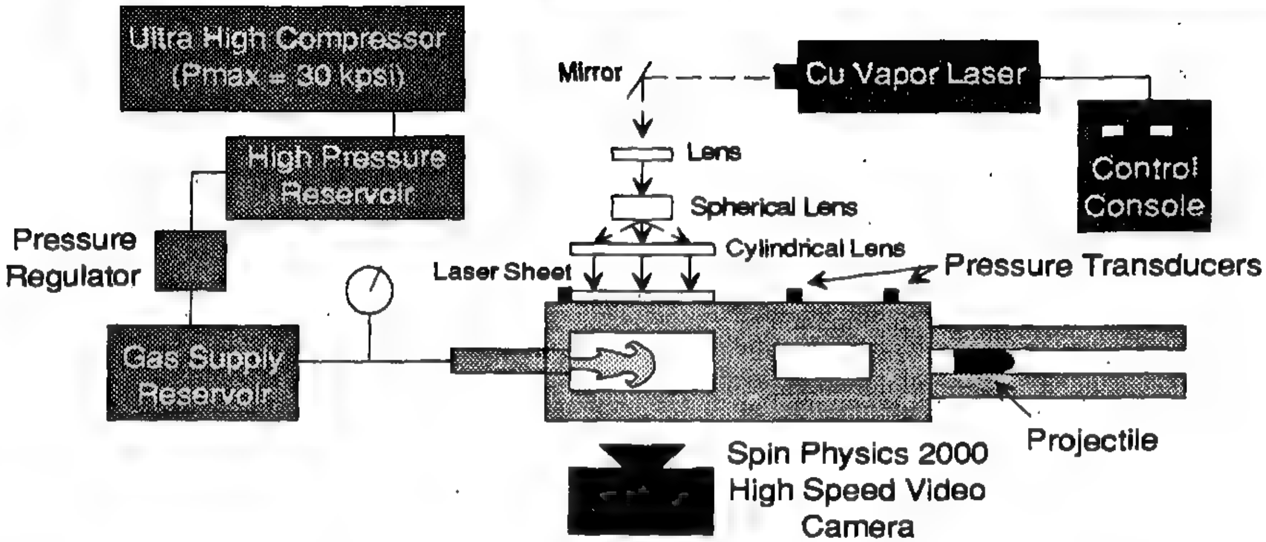
June 25, 1991

FMC

Phenomenology Experiments

Jet Penetration Tests

SAIC
An Employee Owned Company

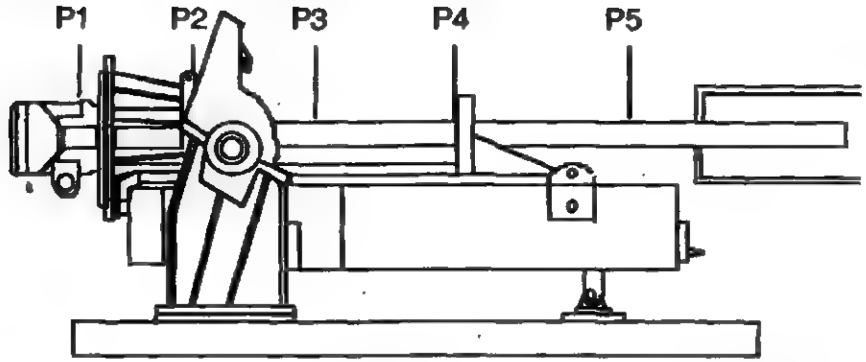


- Measure instantaneous gas jet contours and entrainment processes at near gun pressures (up to 30 kpsi)
- Assess shear layer stripping and droplet generation
- Provide input data for model verification

FMC

DNA 60mm Shot 26

SAIC
An Employee Owned Company

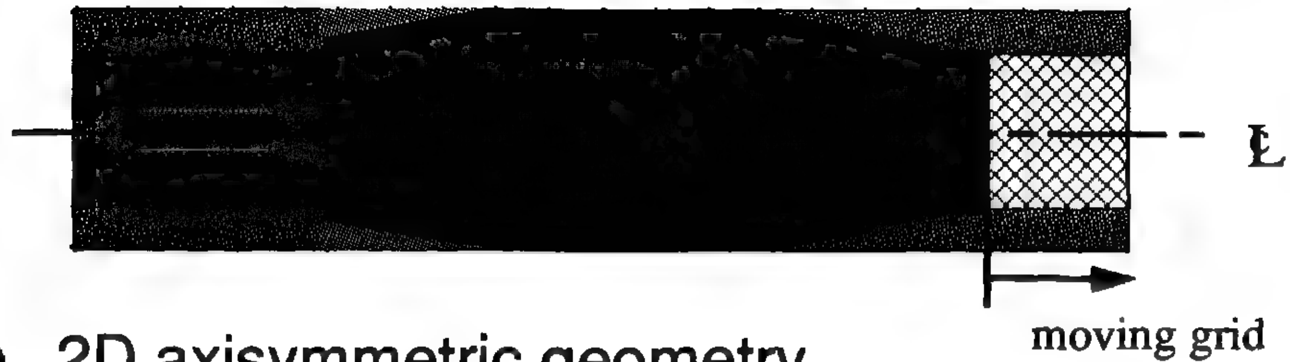


60 mm Subscale Gun Fixture

Electric Energy:	0.8 MJ
Chemical Energy:	4.7 MJ
Elec. Pulse Width:	4 msec
Projectile Mass:	2.75 kg
Muzzle Energy:	1.23 MJ

July 9, 1991

Computational Set-Up



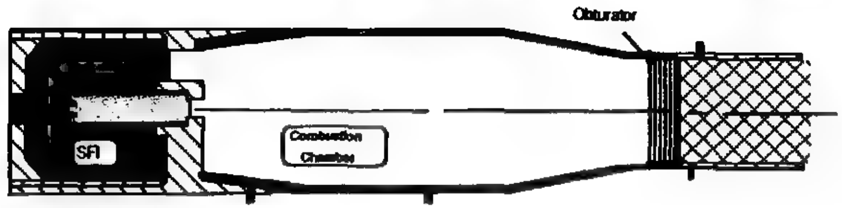
- 2D axisymmetric geometry
- SFI annular orifices (3) are replaced by an annular ring having the same surface area
- 5 species: C_8H_{18}, H_2O_2, H_2O, CO_2, and Air are included in the computation
- 4 material regions: plasma channel, polyethylene tube, fuel rich (SFI), and fuel lean propellant (combustion chamber), are in the computation

July 9, 1991

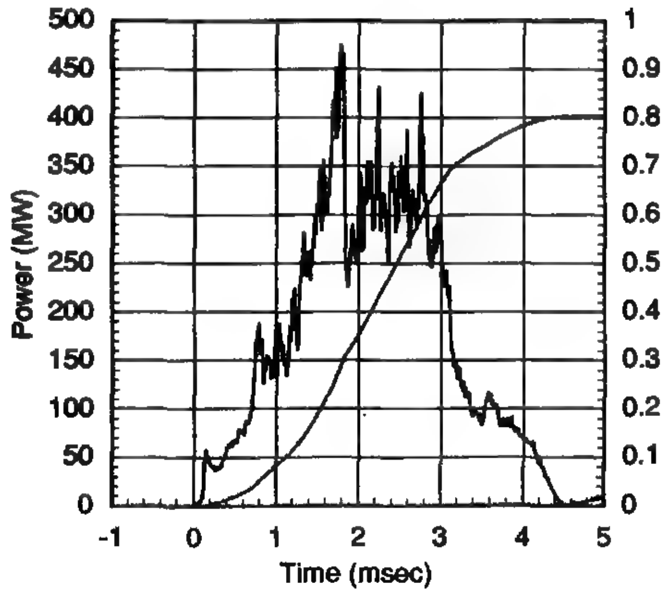
FMC

Capillary & SFI Modeling

SAIC An Employee Owned Company



- Electrical energy data from FMC experiments are directly linked to the computation
- Time delay for fuse-wire breakdown is accounted for
- Material strength of polyethylene tube is ignored
- Plasma channel growth is correlated to electrical energy input



July 9, 1991

FMC

Reaction Chamber Modeling

SAIC
An Employee Owned Company

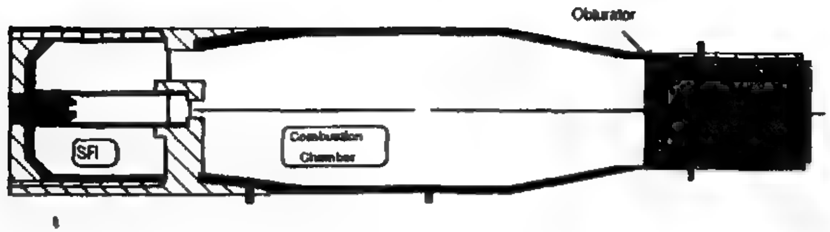
- Flow field in combustion chamber is directly coupled with plasma capillary and SFI
- Chemical kinetic rates are assumed to be fast with respect to turbulent mixing (implies combustion is mixing controlled)
- Single step chemical reaction is assumed

July 9, 1991

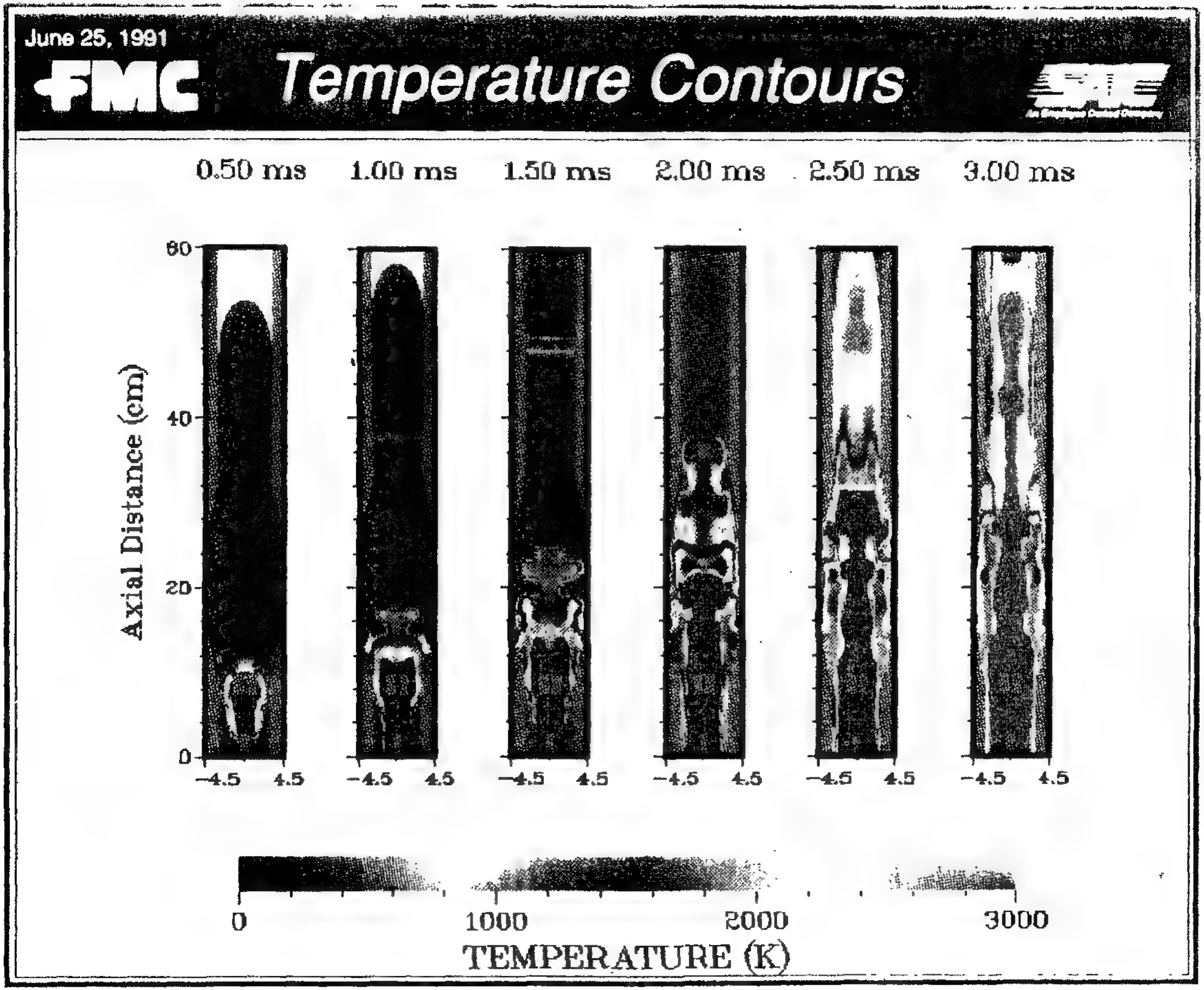
FMC

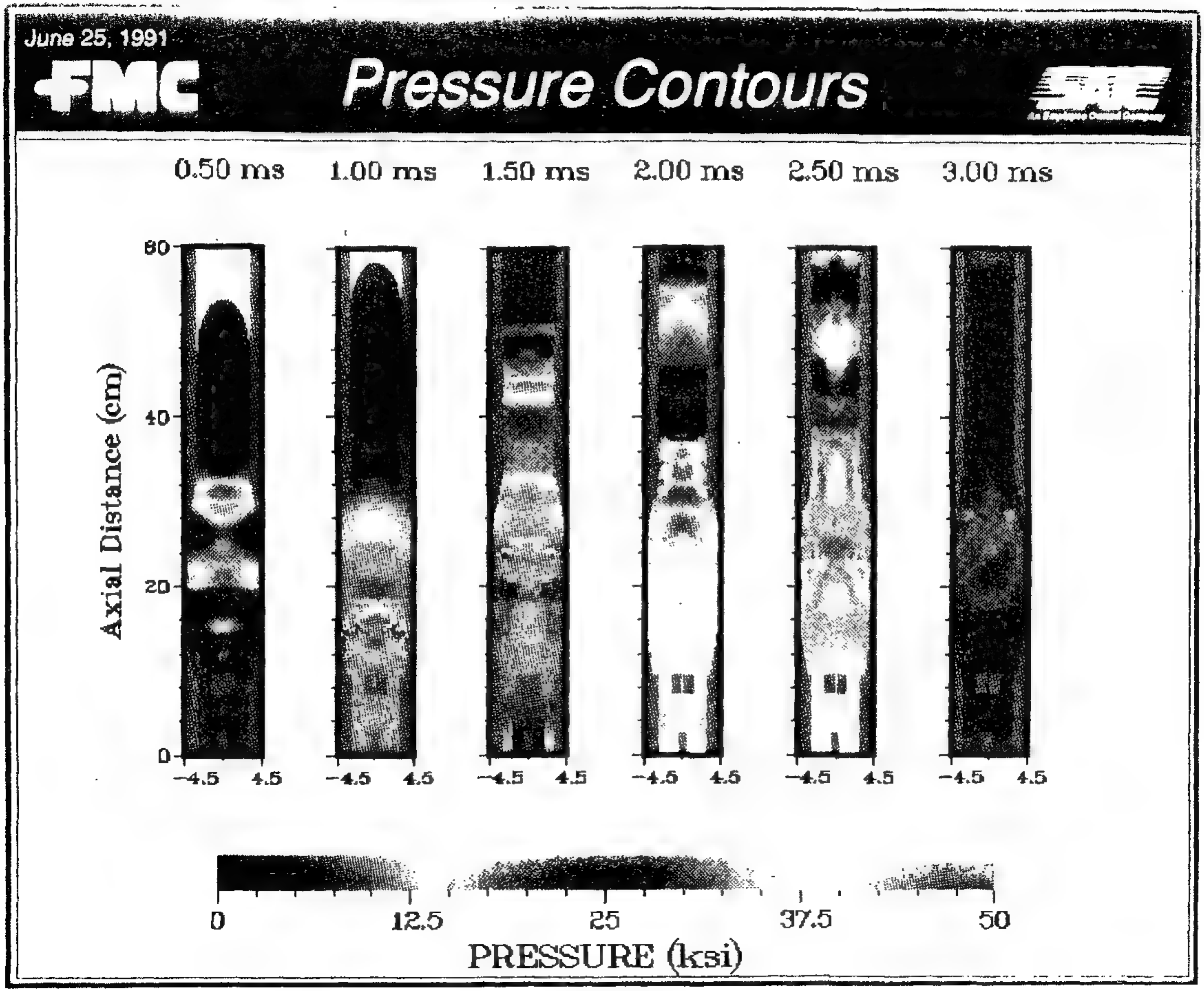
Projectile Dynamics Modeling

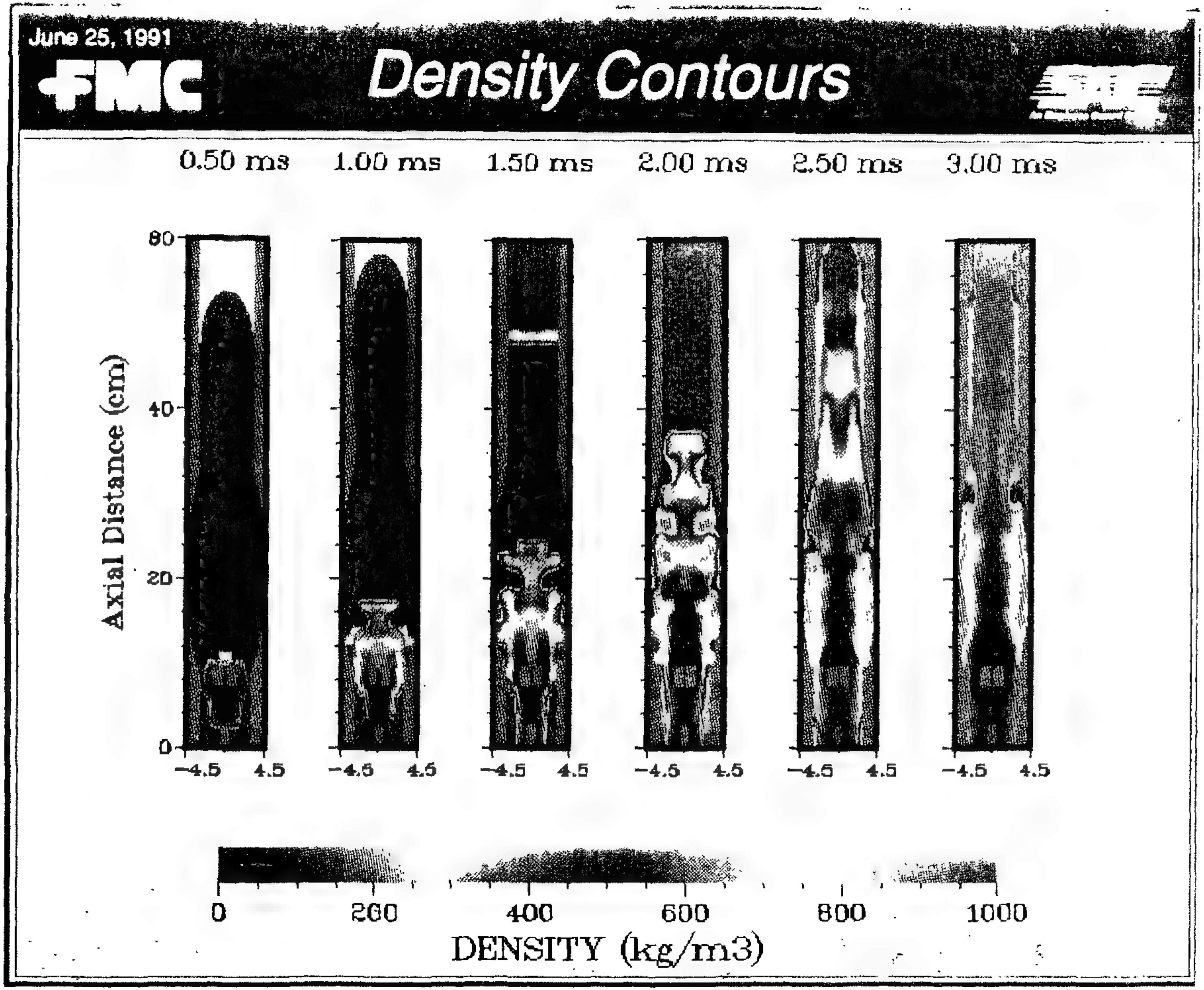
SAIC
An Employee Owned Company

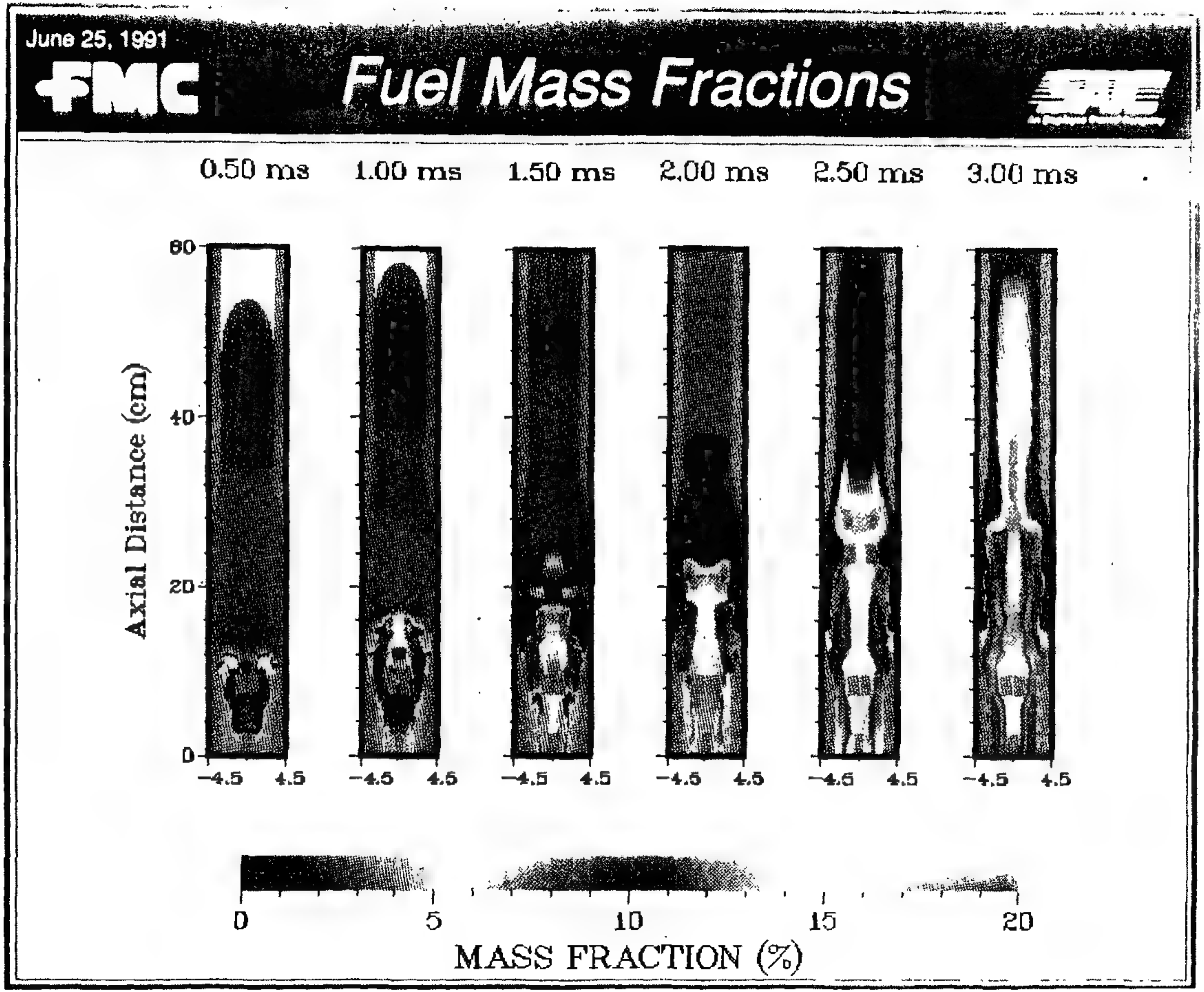


- Dynamic rezoning follows projectile motion
- Problem geometry is reconstructed according to new grid
- Air ahead of projectile is ignored (error < 1%)
- Bore friction force is neglected


June 25, 1991
FMC
Temperature Contours
0.50 ms
1.00 ms
1.50 ms
2.00 ms
2.50 ms
3.00 ms
Axial Distance (cm)
0
20
40
60
-4.5
4.5
0
1000
2000
3000
TEMPERATURE (K)


June 25, 1991
FMC
Pressure Contours
0.50 ms
1.00 ms
1.50 ms
2.00 ms
2.50 ms
3.00 ms
Axial Distance (cm)
0
20
40
60
-4.5
4.5
0
12.5
25
37.5
50
PRESSURE (ksi)

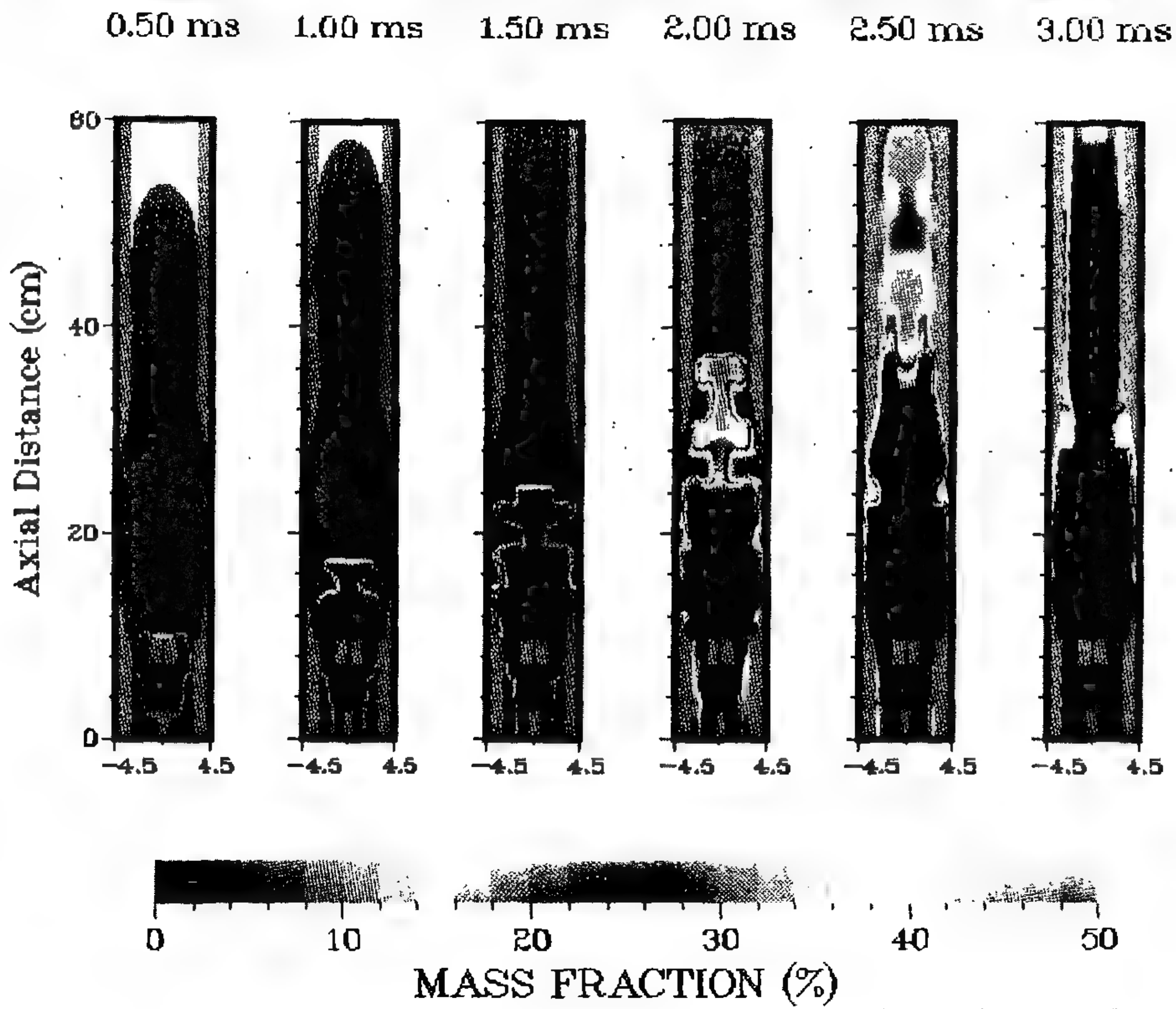

June 25, 1991
FMC
Density Contours
0.50 ms
1.00 ms
1.50 ms
2.00 ms
2.50 ms
3.00 ms
Axial Distance (cm)
80
40
20
0
-4.5
4.5
0
200
400
600
800
1000
DENSITY (kg/m3)

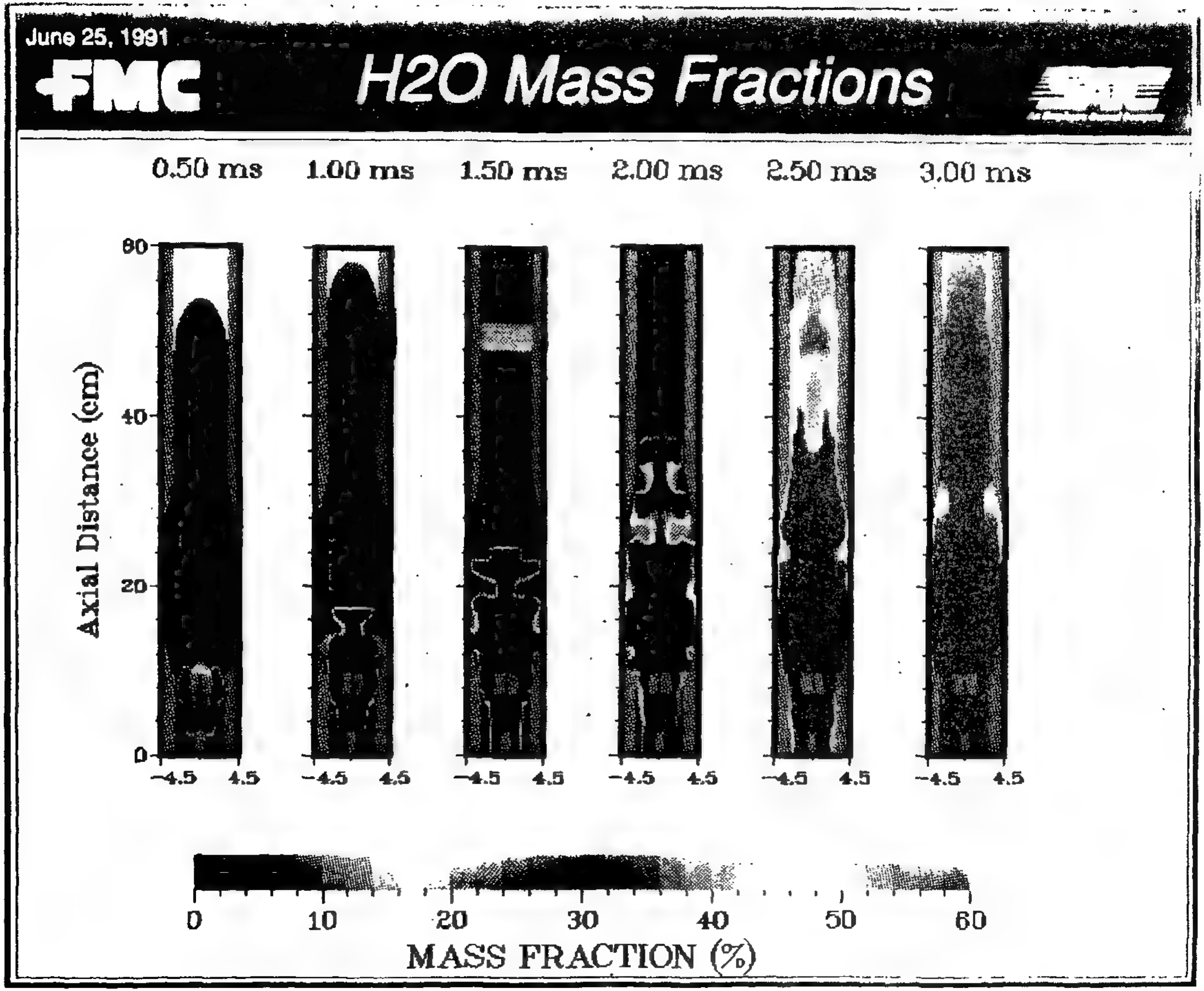

June 25, 1991
FMC
Fuel Mass Fractions
0.50 ms
1.00 ms
1.50 ms
2.00 ms
2.50 ms
3.00 ms
Axial Distance (cm)
60
40
20
0
−4.5
4.5
0
5
10
15
20
MASS FRACTION (%)

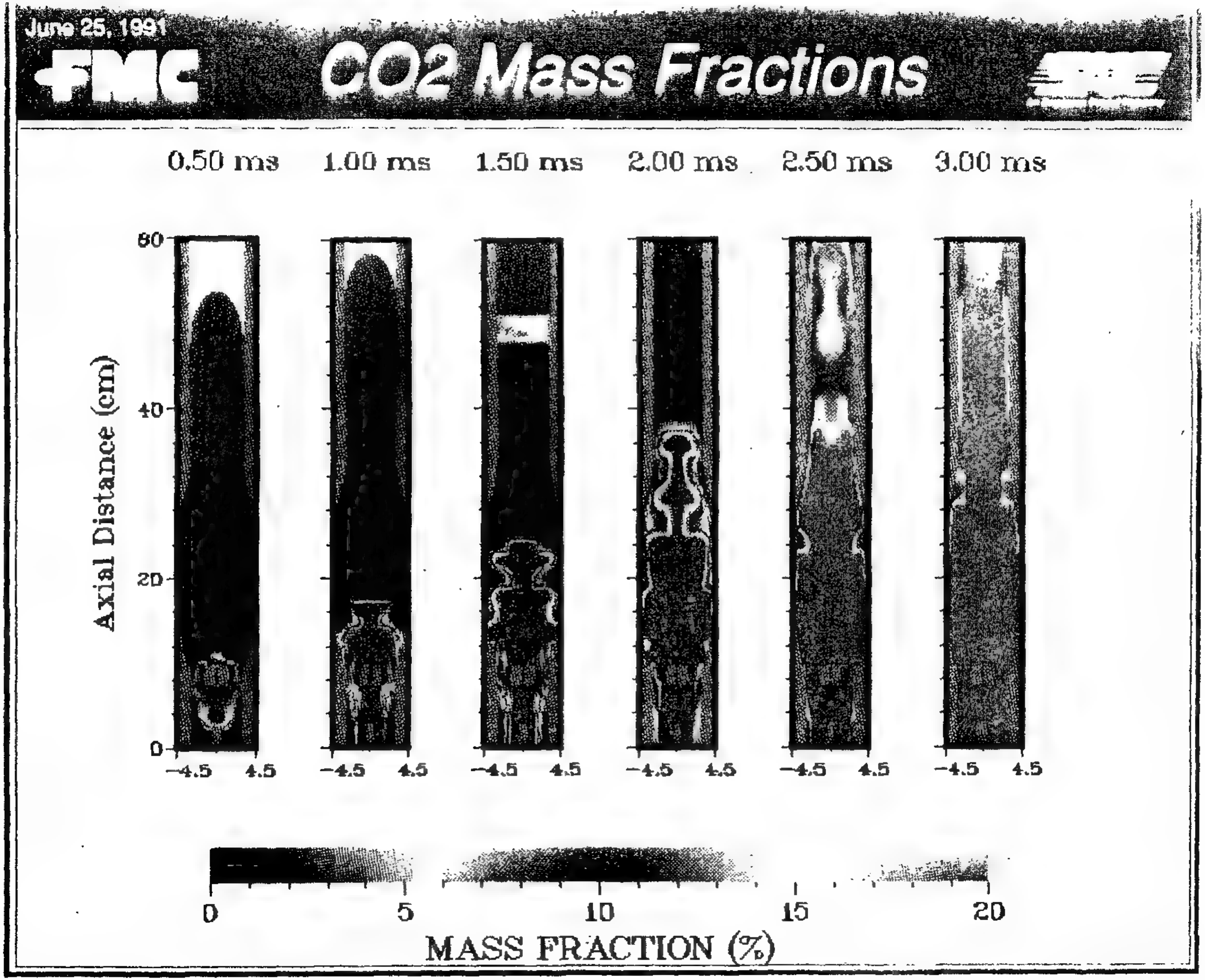
June 25, 1991

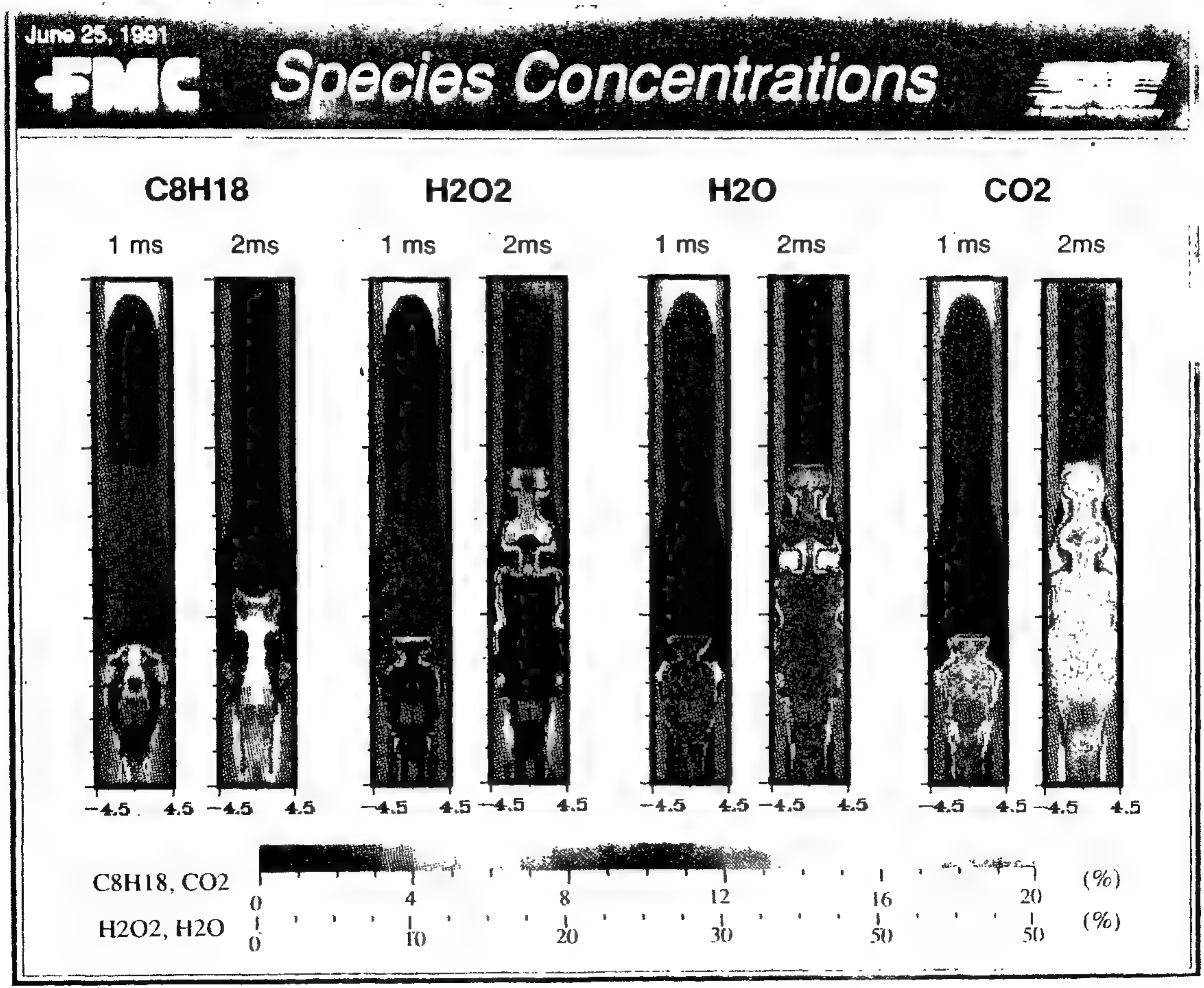
FMC

Oxidizer Mass Fractions




June 25, 1991
FMC
H2O Mass Fractions
0.50 ms
1.00 ms
1.50 ms
2.00 ms
2.50 ms
3.00 ms
Axial Distance (cm)
0
20
40
60
-4.5
4.5
0
10
20
30
40
50
60
MASS FRACTION (%)


June 25, 1991
FMC
CO2 Mass Fractions
0.50 ms
1.00 ms
1.50 ms
2.00 ms
2.50 ms
3.00 ms
Axial Distance (cm)
60
40
20
0
-4.5
4.5
0
5
10
15
20
MASS FRACTION (%)


June 25, 1991
FMC
Species Concentrations
C8H18
H2O2
H2O
CO2
1 ms
2ms
1 ms
2ms
1 ms
2ms
1 ms
2ms
-4.5 4.5 -4.5 4.5 -4.5 4.5 -4.5 4.5 -4.5 4.5 -4.5 4.5 -4.5 4.5 -4.5 4.5
C8H18, CO2
0 4 8 12 16 20
(%)
H2O2, H2O
0 10 20 30 50 50
(%)

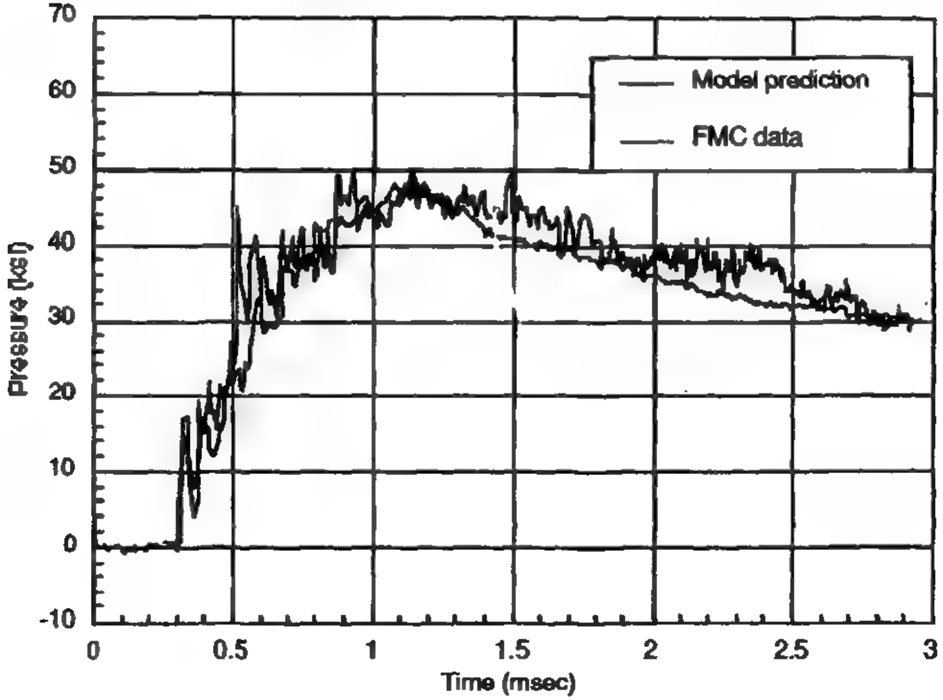
July 9, 1991

FMC

Pressure Waveform Comparison

SAIC
An Employee Owned Company

P1



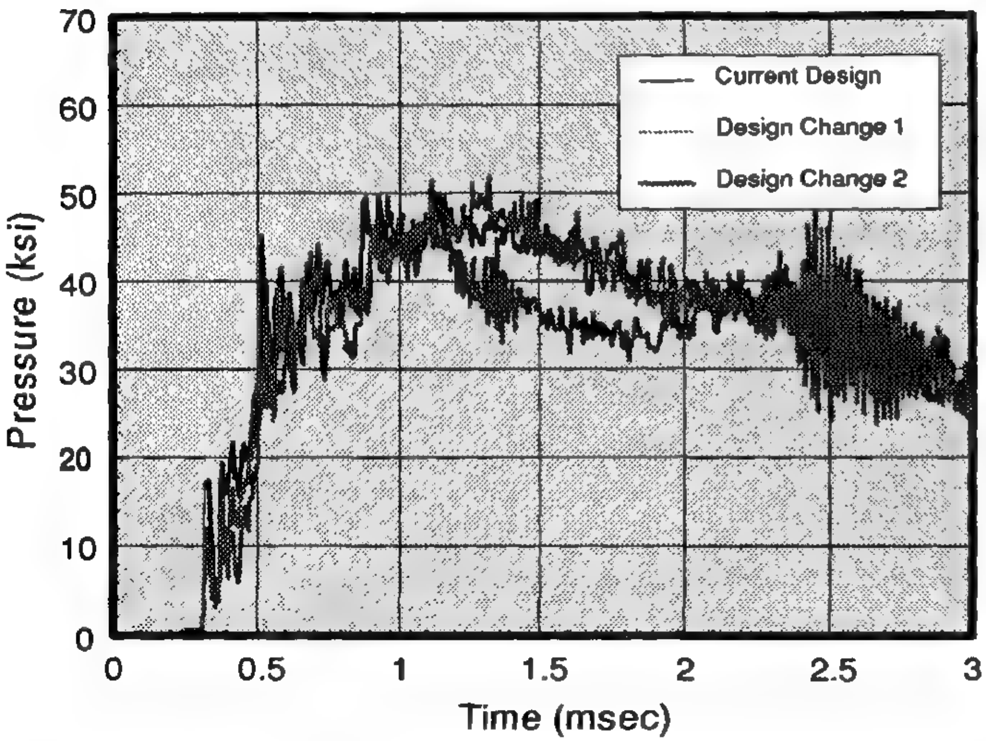
June 25, 1991

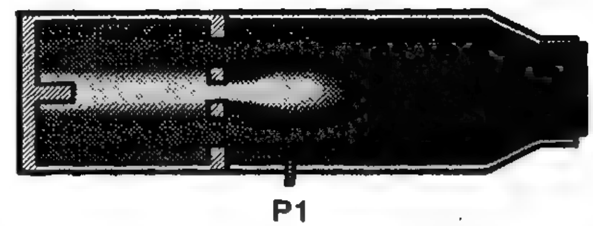
FMC

SFI Performance Studies

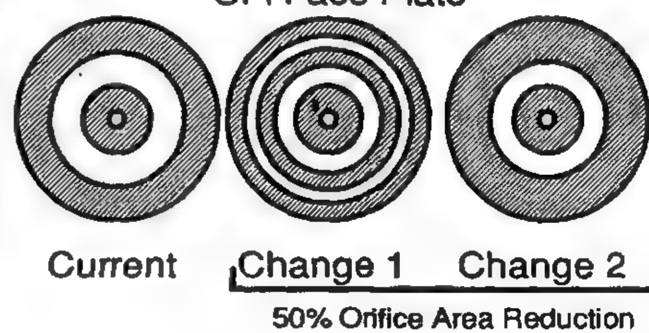
SAIC
An Employee Owned Company

Pressure Transducer P1





SFI Face Plate



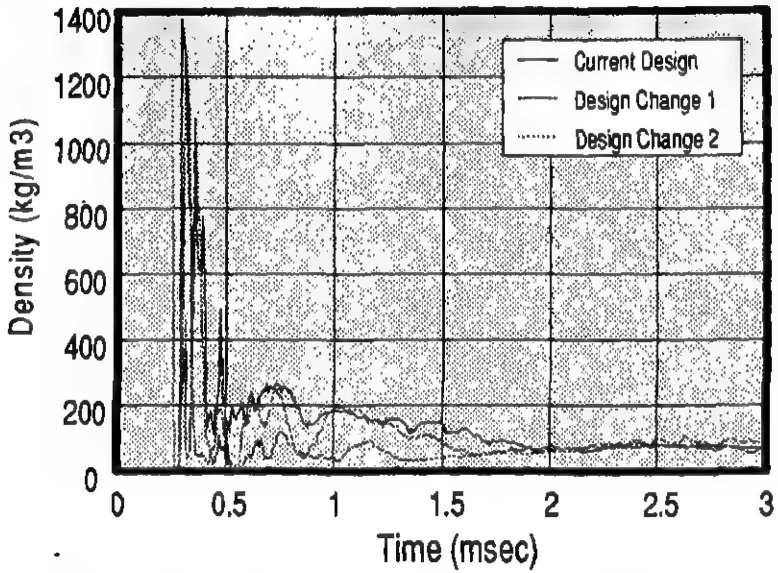
June 25, 1991

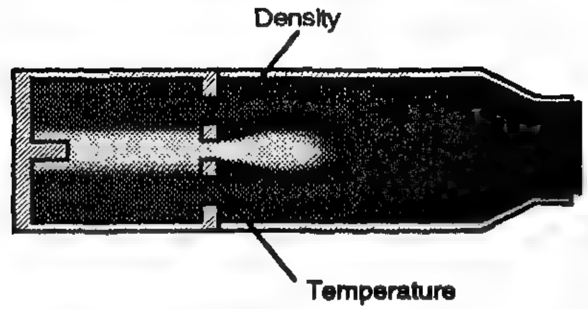
FMC

SFI Performance Studies

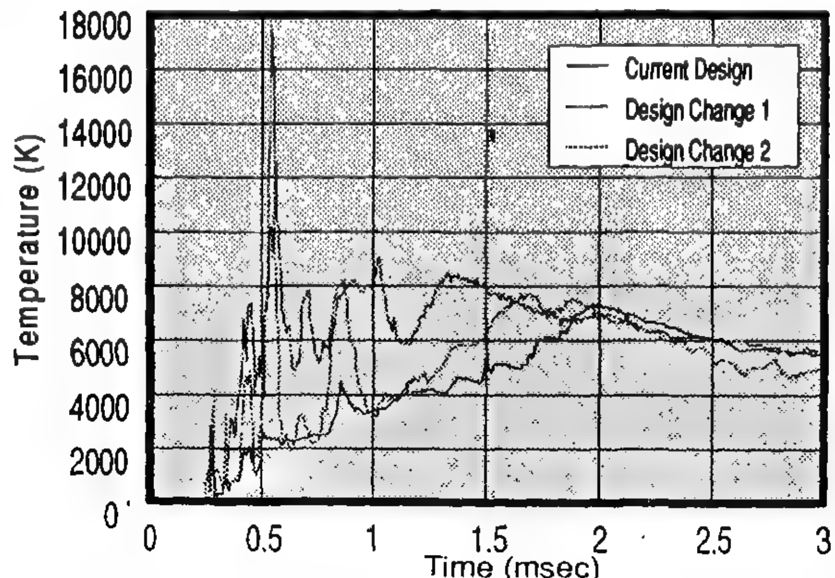
SAIC
An Employee Owned Company

Fuel Jet Density

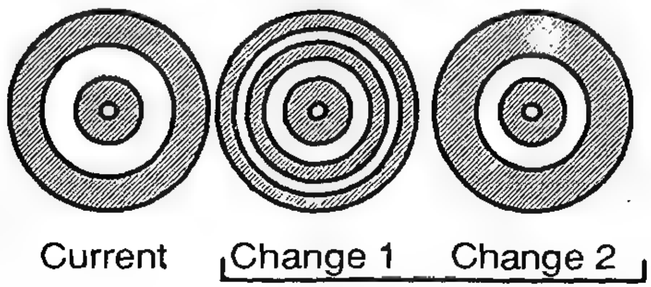




Fuel Jet Temperature



SFI Face Plate



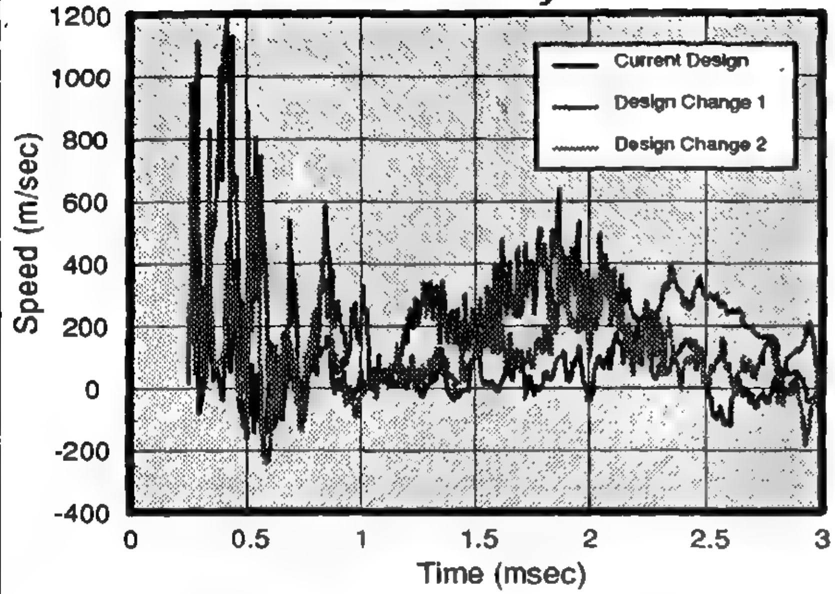
June 25, 1991

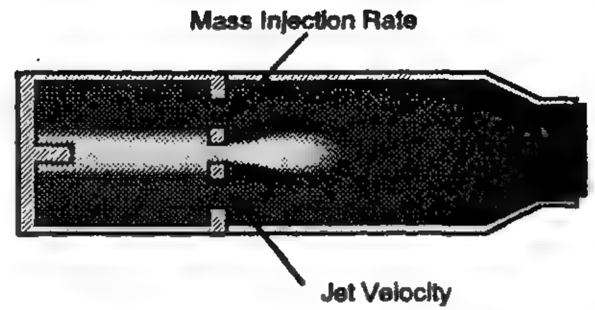
FMC

SFI Performance Studies

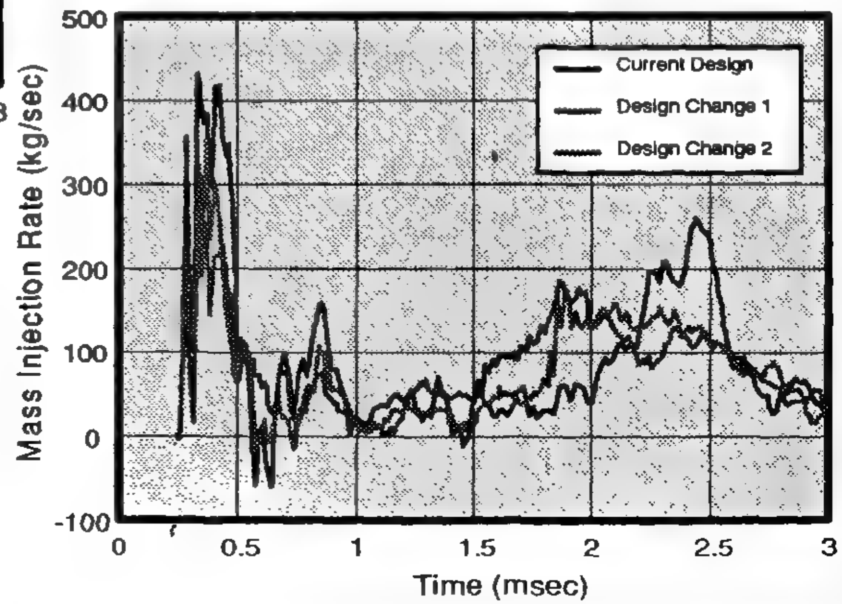
SAIC
An Employee Owned Company

Jet Velocity

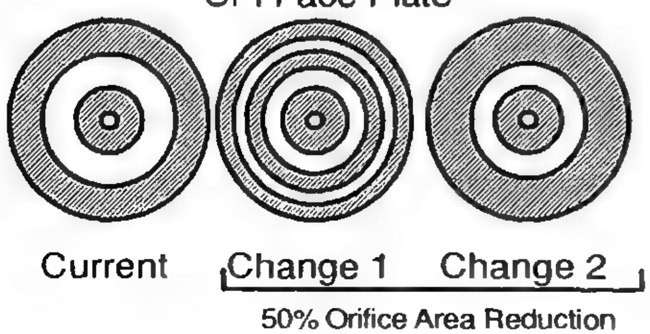


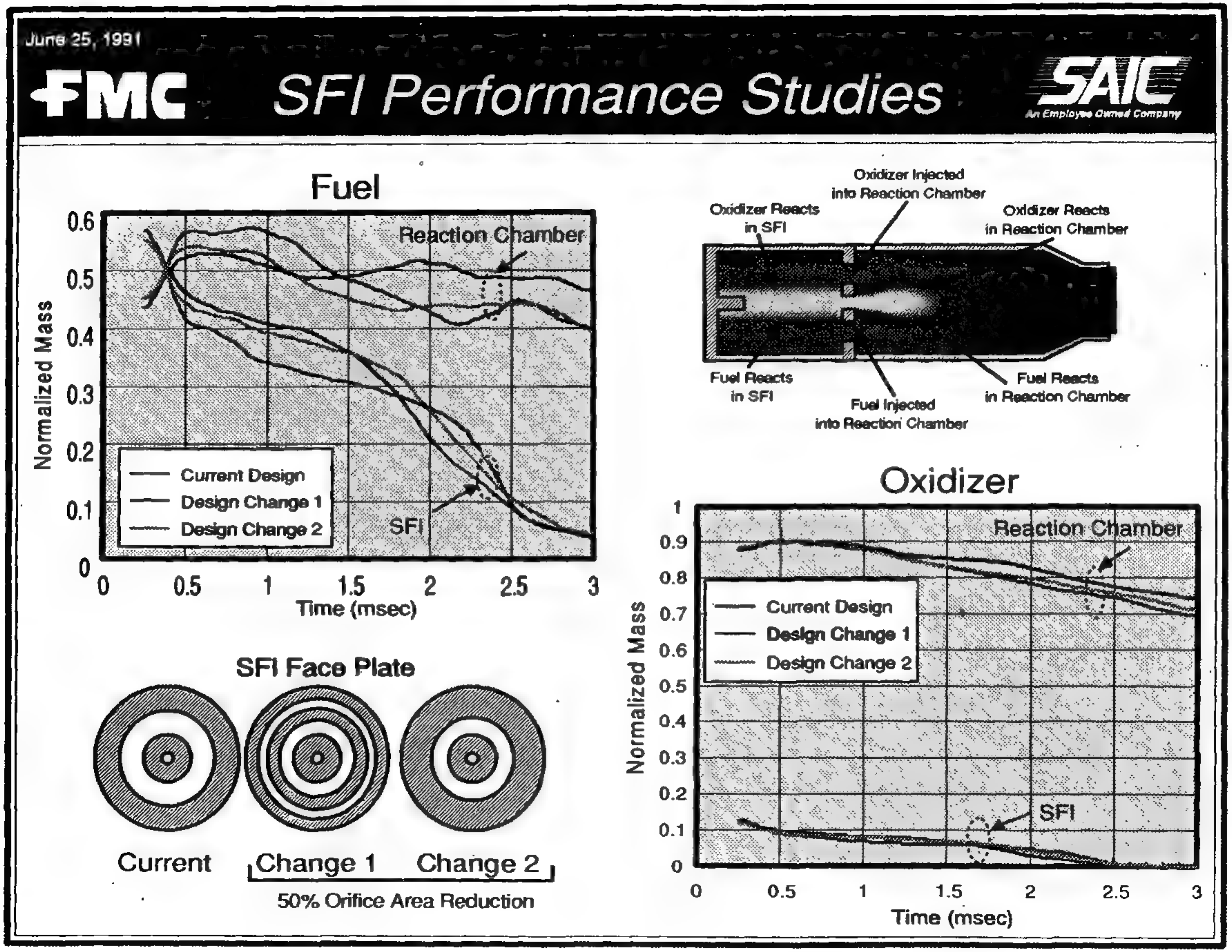


Mass Injection Rate



SFI Face Plate




June 25, 1991
FMC
SFI Performance Studies
SAIC
An Employee Owned Company
Fuel
Reaction Chamber
SFI
Normalized Mass
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
Time (msec)
Current Design
Design Change 1
Design Change 2
Oxidizer Injected into Reaction Chamber
Oxidizer Reacts in SFI
Oxidizer Reacts in Reaction Chamber
Fuel Reacts in SFI
Fuel Injected into Reaction Chamber
Fuel Reacts in Reaction Chamber
Oxidizer
Reaction Chamber
SFI
Normalized Mass
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
Time (msec)
Current Design
Design Change 1
Design Change 2
SFI Face Plate
Current
Change 1
Change 2
50% Orifice Area Reduction

PHYSICS OF ETC PLASMA-FLUID INTERACTIONS

B. A. Kashiwa, H. A. Davis, and R. J. Trainor, Jr.
Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

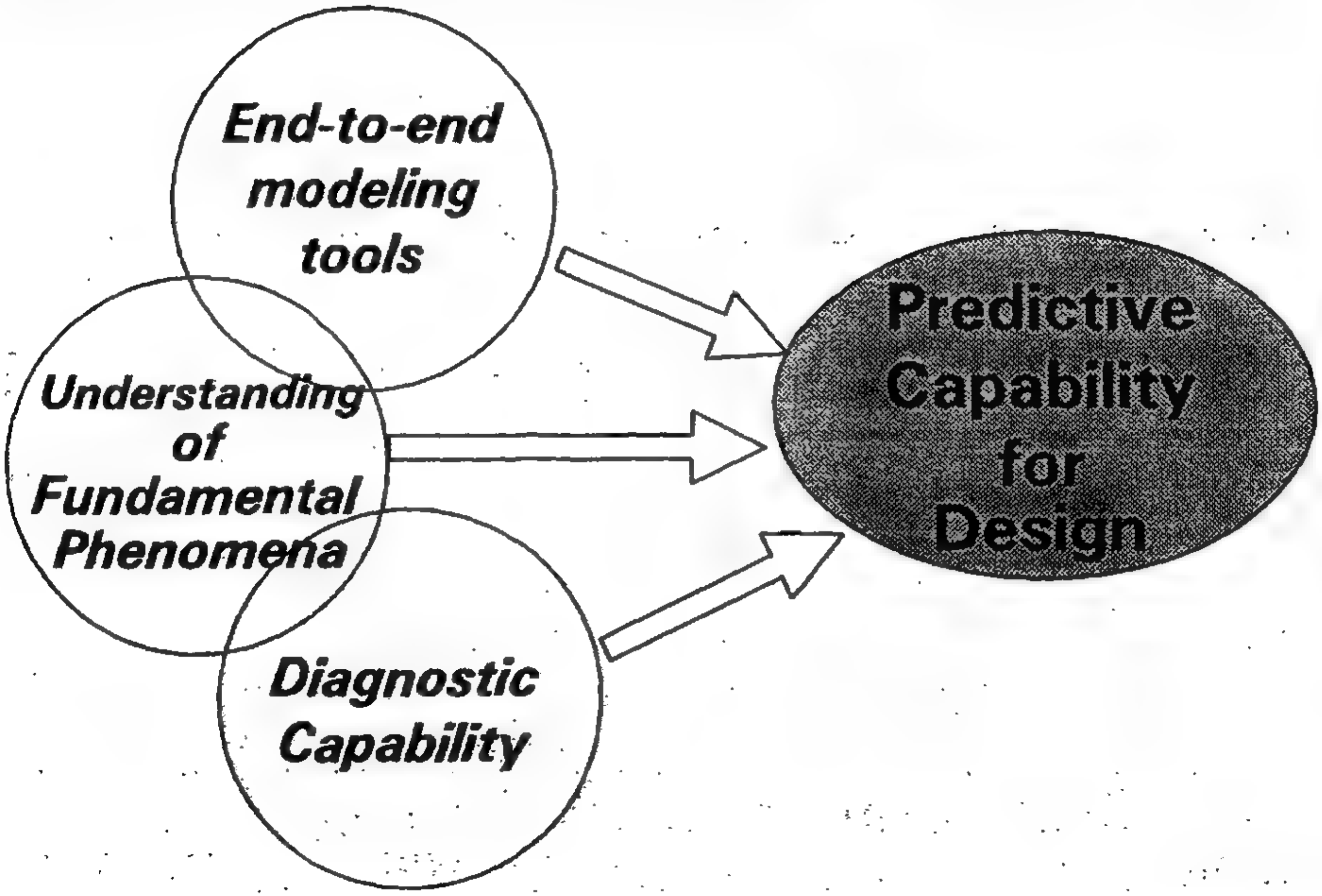
Two fundamental elements of the Electrothermal/Chemical (ETC) Gun process are discussed. The first involves the nature of discharge arc itself, and the second involves the microphysical interaction of the expanding hot gas with a cool condensed phase propellant. Magnetohydrodynamic calculations suggest the existence of a so-called filament discharge in the hot expanding gas. These calculations are discussed. Also, recent experimental evidence suggests the importance of Rayleigh-Taylor instability in the development of a cavity in a liquid, at prototypical ETC Gun pressures. The latest multidimensional hydrodynamic analysis of this instability effect is presented.

B. A. Kashiwa, H. A. Davis, and R. J. Trainor
Los Alamos National Laboratory

Physics of ETC Plasma-Fluid Interactions

JANNAF Workshop
July 9-11, 1991
Aberdeen, Md

Los Alamos Goal Is
Predictive Capability For ETC Design



Overview of Los Alamos ETC Activities

Working Toward A Predictive Capability

1. End-to-end code development
2. Benchmarking expts. on 20 mm ET gun

This talk

3. Plasma-working fluid interaction expts.
4. Modeling of P/W-F experiments

Hal Davis next talk

5. Projectile velocity diagnostics -- *Dick Bartsch tomorrow AM*

Los Alamos ETC Code Uses Multidimensional Hydrocode Library

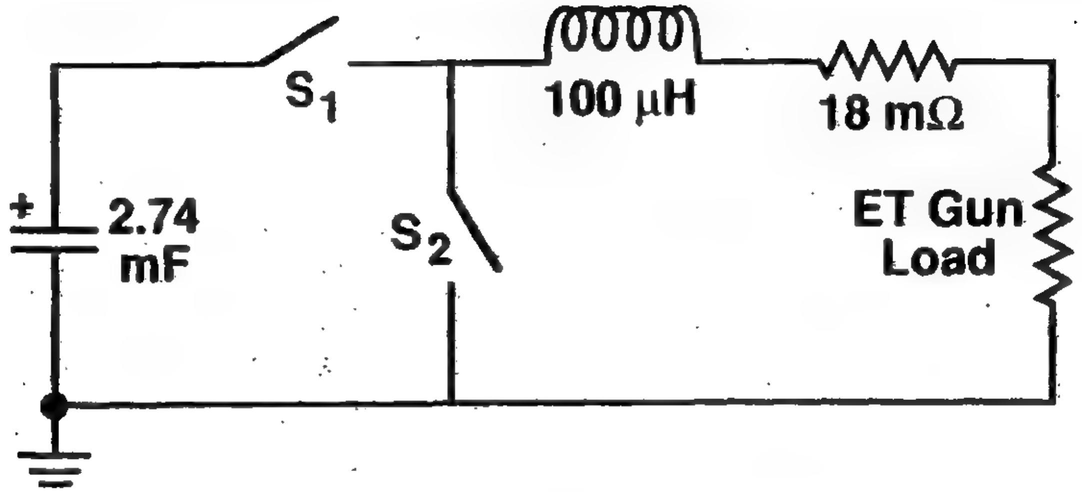
- End-to-end code combines hydrocode library (CFDLIB), circuit code analysis and capillary plasma tube model.
  - Useful engineering analysis tool
  - Now developing into wide-range predictive tool

- Gun chamber and tube treated with multidimensional code which treats a turbulent, chemically-reacting, multispecies fluid
  - Predominantly Eulerian frame used
  - Two propellant burn models (Arrhenius & bulk burn)
  - Can access variety of modules (e.g., turbulence, EOS)

- Reference on interfaces, numerical techniques, models:
  B. A. Kashiwa et al., Proc. 27th JANNAF Combust. Mtg., 1990

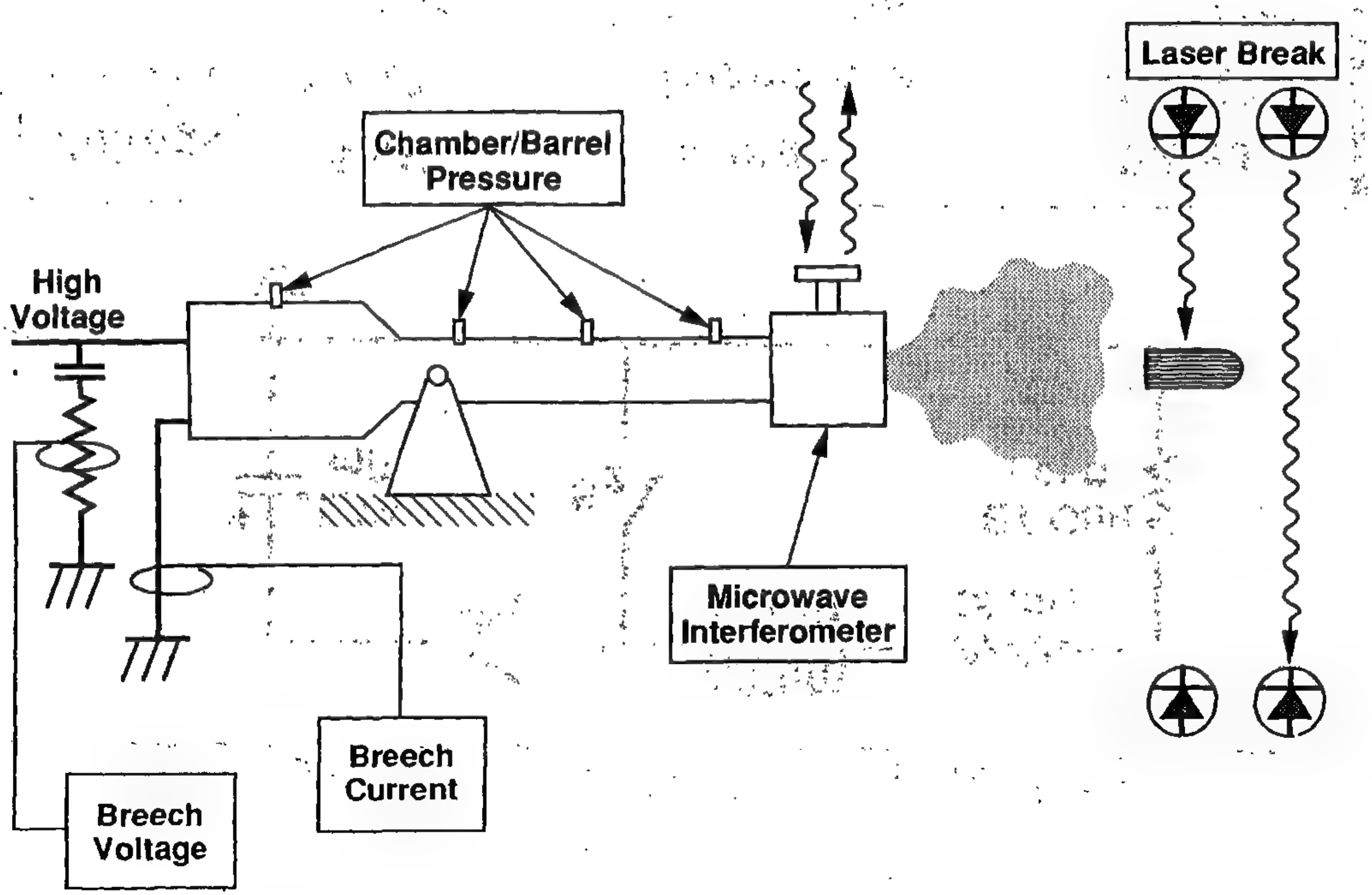
Los Alamos 20 mm ET Gun

Used For Code Benchmarking

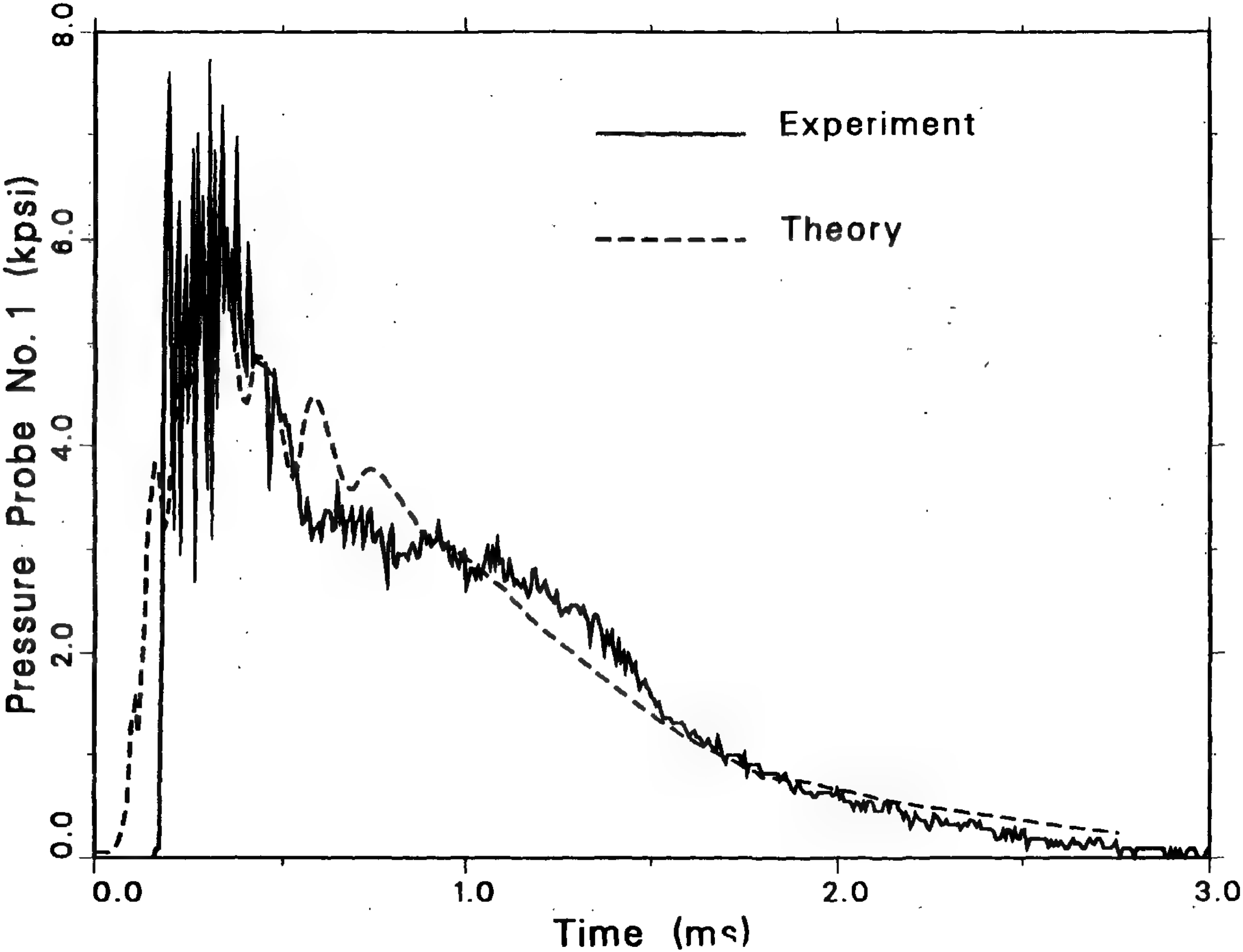


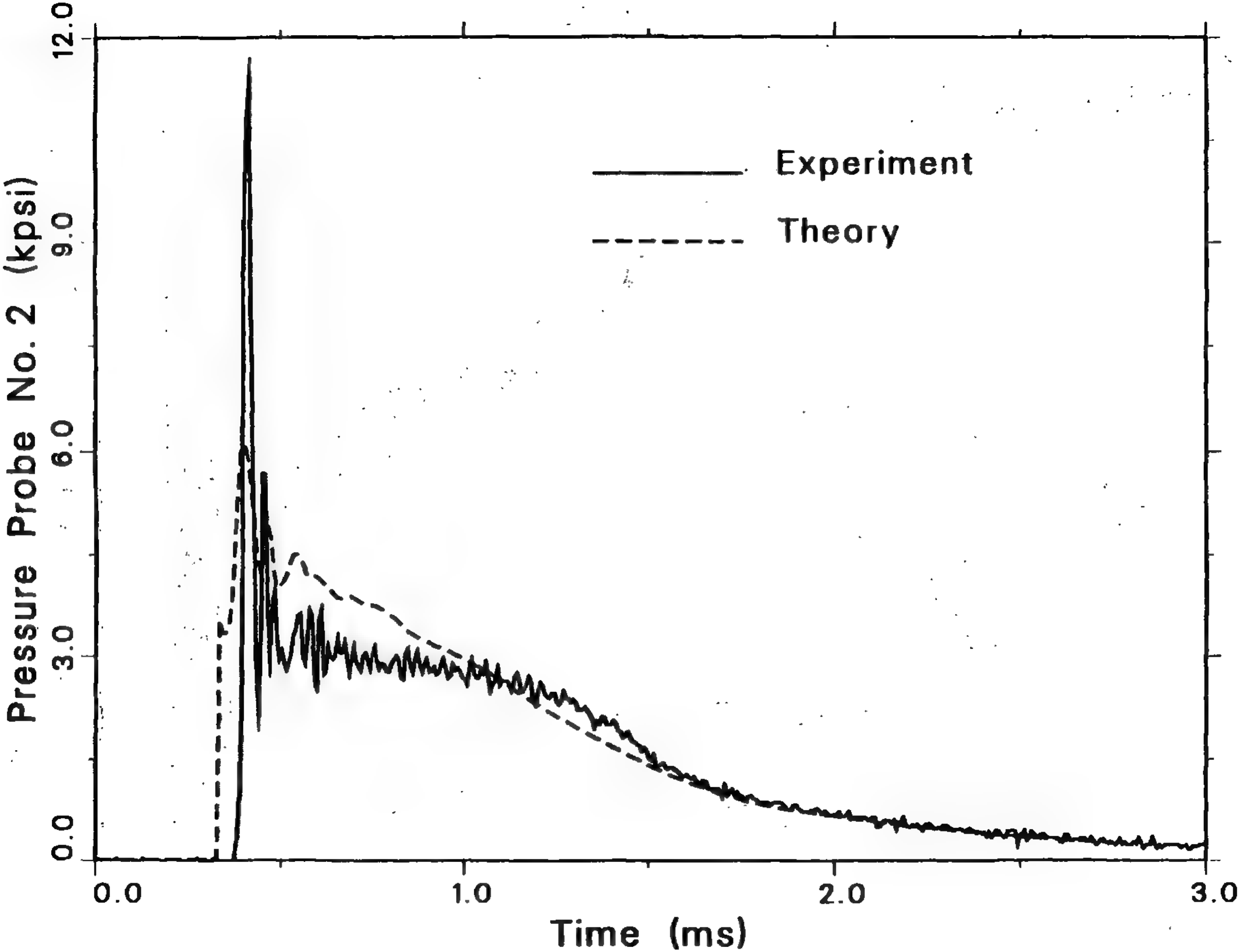
Voltage	4 kV	Energy	22 kJ
Current	10 kA	Impedance	0.2 Ω
Power	22 MW	Max. velocity	0.6 km/s
Rise time	0.6 ms	Max. pressure	6 kpsi

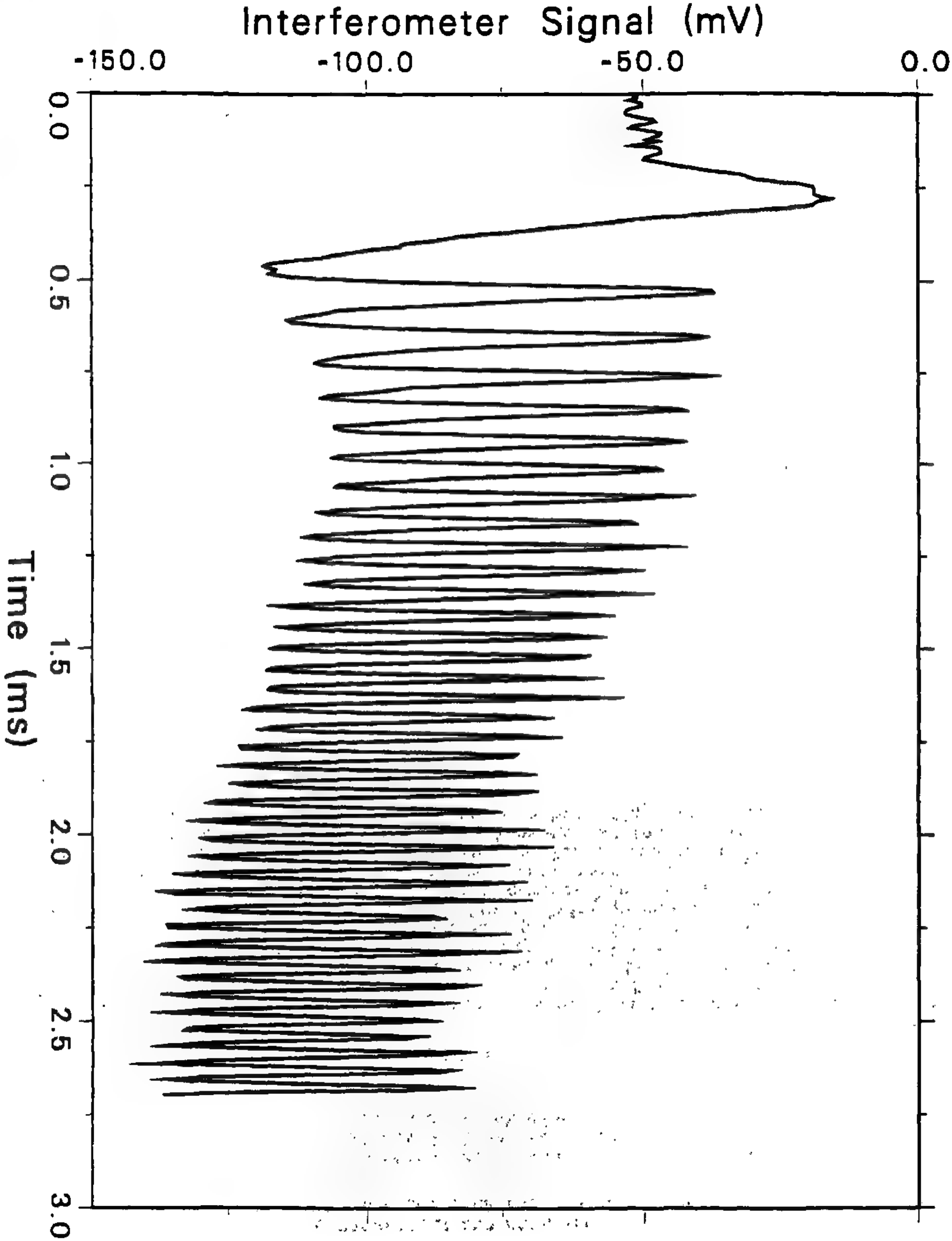
Los Alamos ET Gun Diagnostics



Los Alamos


Experiment
Theory
Pressure Probe No. 1 (kpsi)
0.0
2.0
4.0
6.0
8.0
0.0
1.0
2.0
3.0
Time (ms)


Experiment
Theory
Pressure Probe No. 2 (kpsi)
0.0
3.0
6.0
9.0
12.0
Time (ms)
0.0
1.0
2.0
3.0


Interferometer Signal (mV)
-150.0
-100.0
-50.0
0.0
Time (ms)
0.0
0.5
1.0
1.5
2.0
2.5
3.0

OBSERVATIONS AND MODELING OF FUNDAMENTAL ELECTROTHERMAL GUN PHENOMENA

H. A. Davis, R. R. Bartsch, B. A. Kashiwa and N. T. Padial
Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

We have begun experimental studies coupled with computer modeling of fundamental electrothermal gun processes. In initial work, now complete, we used a 20-mm-bore steam driven electrothermal gun to develop diagnostics and to benchmark Los Alamos ET gun computer modeling. Results of current experiments, now underway, to image the interaction of a plasma with a working fluid will be reported. The object is to determine fluid mixing processes, first with non-combustible working fluids and then with combustible fluids. Initially, the interaction of an exploded wire plasma with water is being studies with time-resolved X-ray photography. The interaction is contained in a dielectric chamber surrounded by a steel housing. A short section of barrel is used to allow for fluid expansion. First shots have been fired and images have been produced.

H.A. Davis, R.R. Bartsch,
B.A. Kashiwa, and N.T. Padial
Los Alamos National Laboratory

Observations and Modeling of Fundamental Electrothermal Gun Phenomena

JANNAF Workshop
9-11 July, 1991
Aberdeen, Md

Los Alamos Research Goal

Investigate Fundamental ETC Phenomena

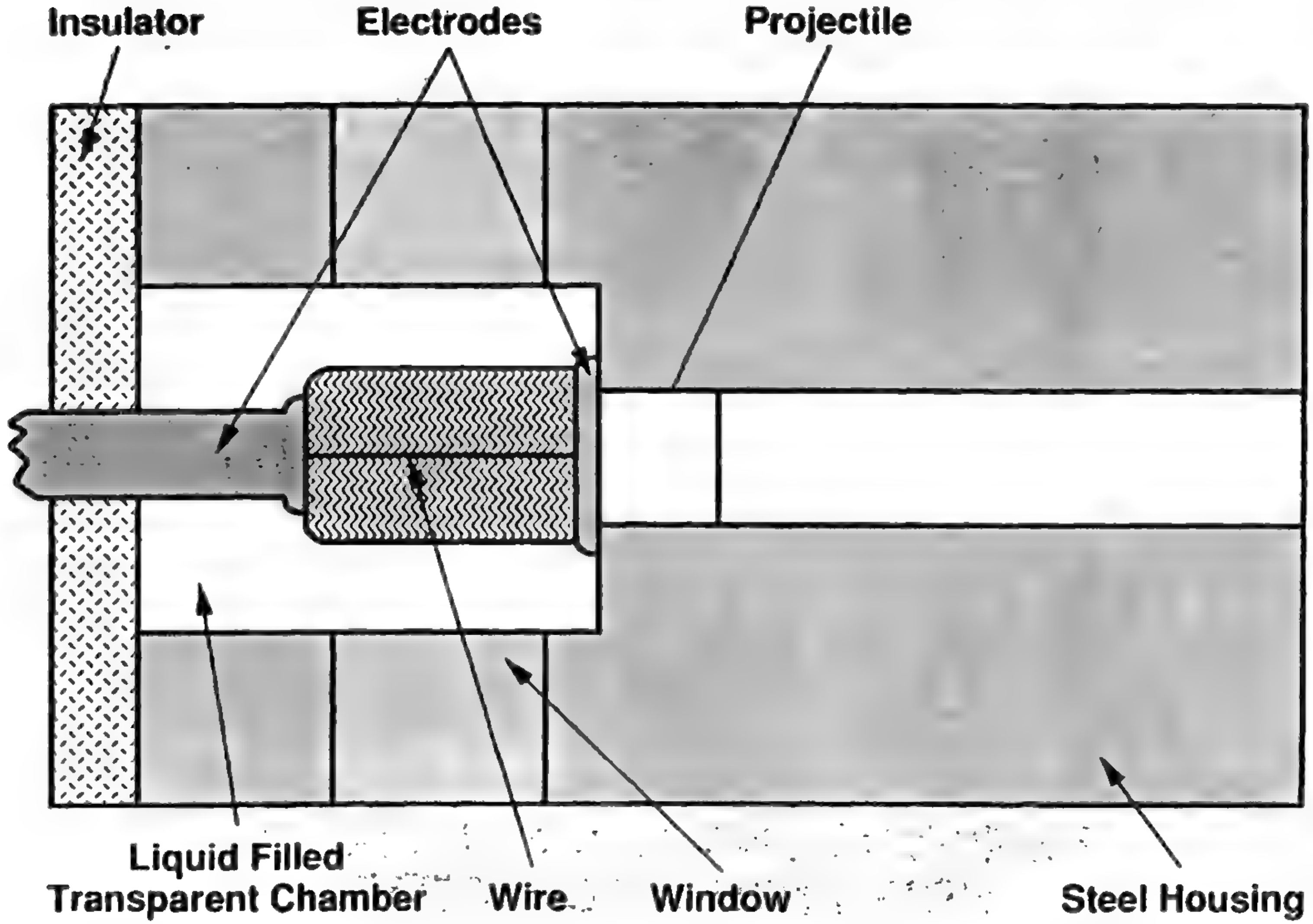
- Understand Mixing and Control Through Well Diagnosed Experiments (Imaged Chambers)

- Develop Predictive Computer Models Using Experimental Observations

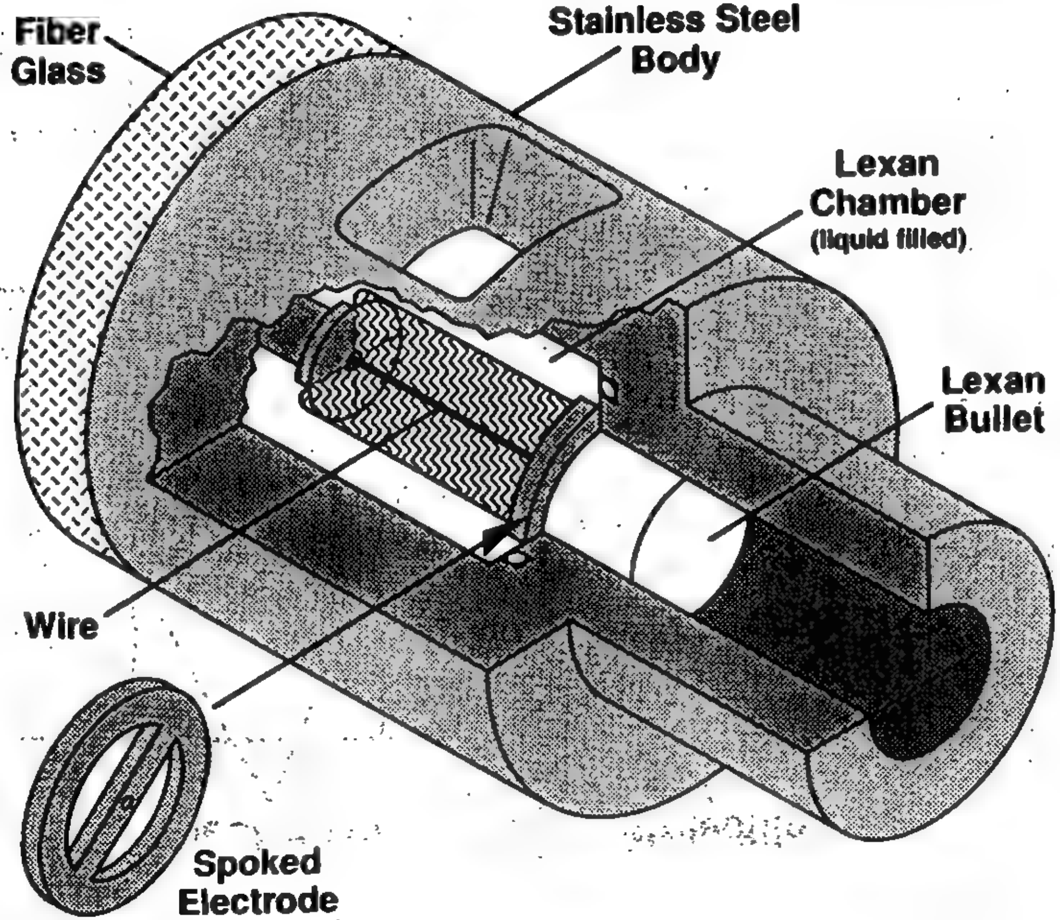
- Approach - Begin with Plasma Embedded in Working Fluid (Inert and Combustible)

Los Alamos

Plasma/Working-Fluid Interacterion Chamber

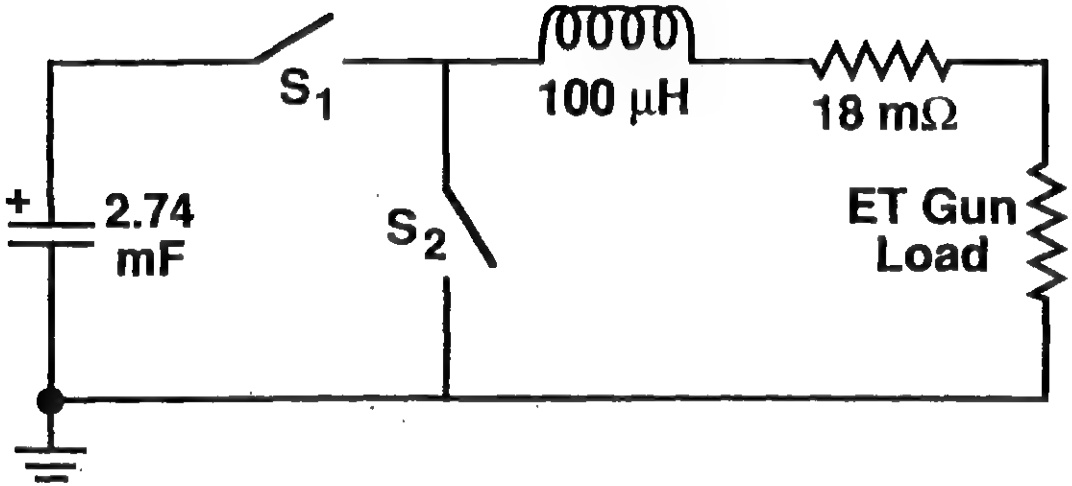


ELECTROTHERMAL GUN WITH TRANSPARENT CHAMBER



Los Alamos

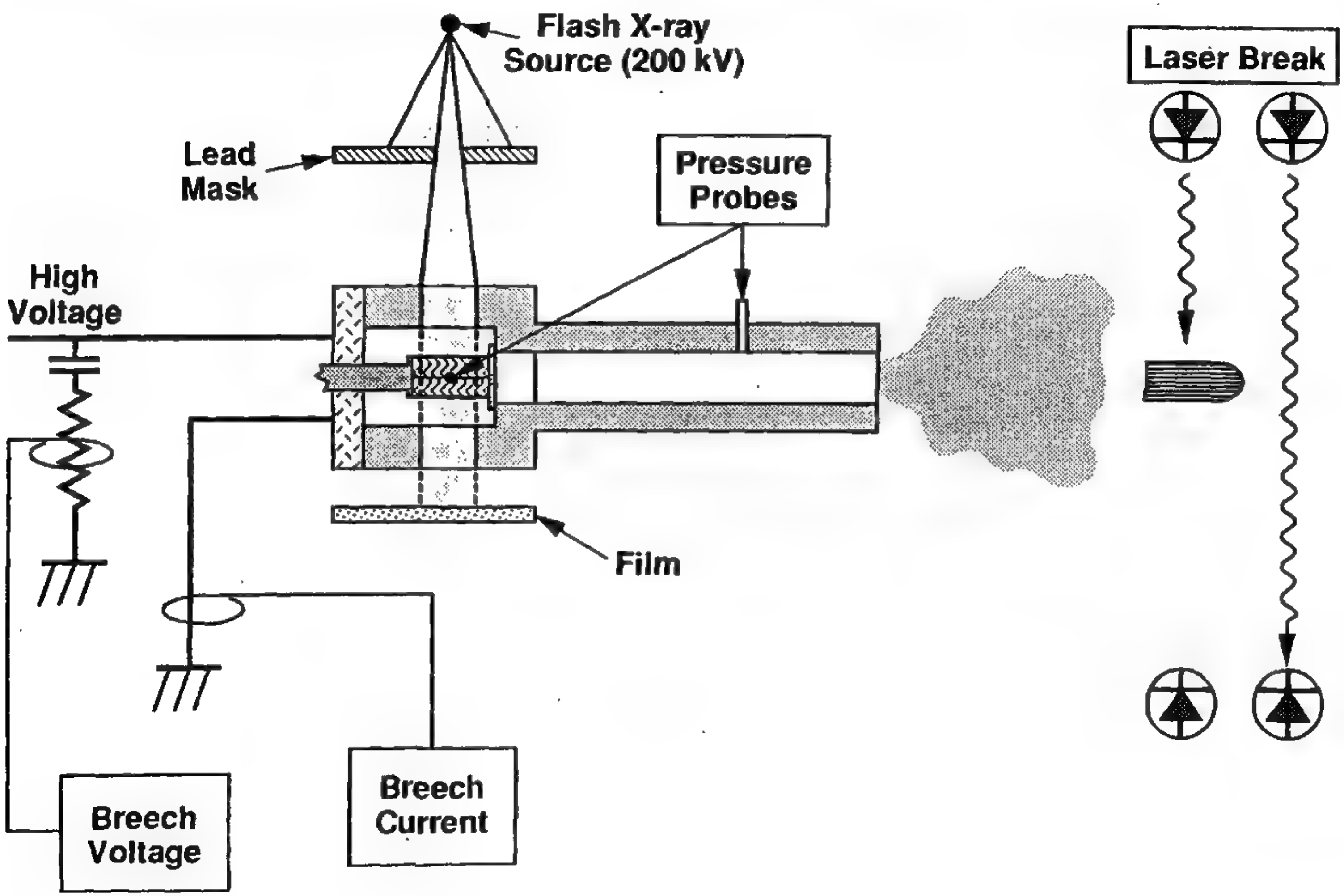
Electrical Drive Circuit



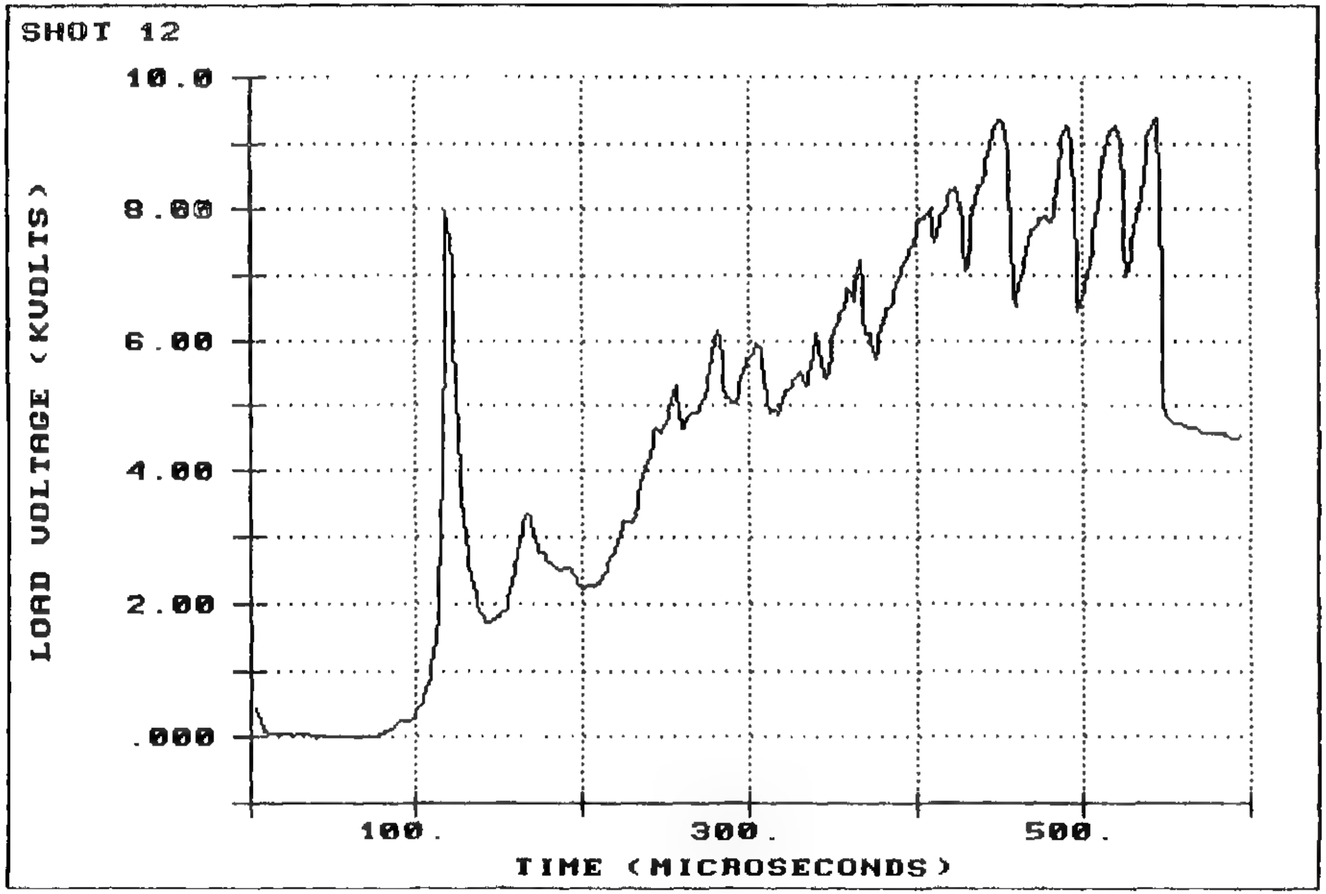
Load Voltage	4-8 kV
Load Current	6 kA
Energy Delivered	10 kJ in 0.5 ms
Peak Pressure	10-20 kpsi
Projectile Velocity	250-300 m/s

Los Alamos

Plasma/Working-Fluid Interacterion Experiment

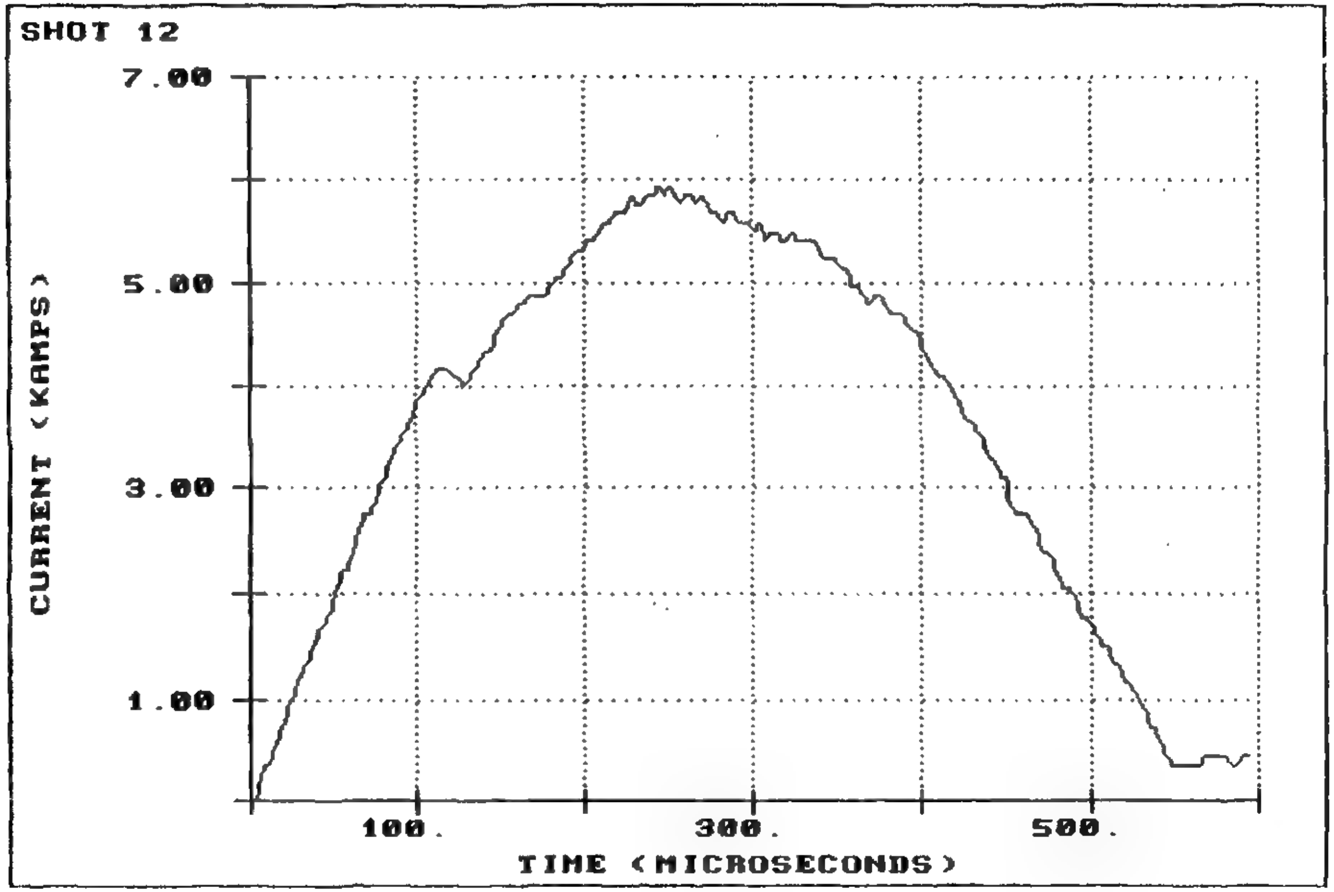


Load Voltage Waveform



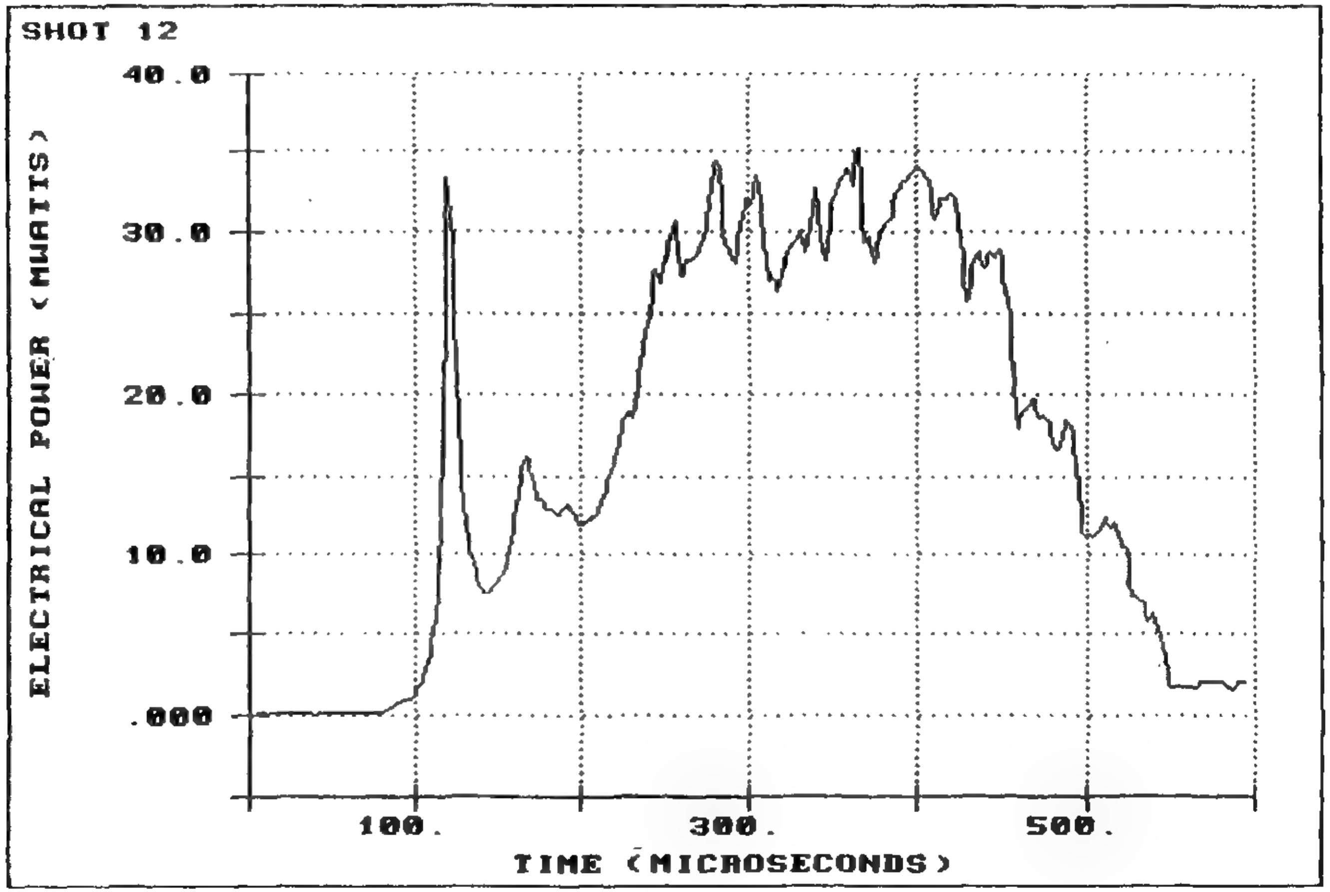
Los Alamos

Load Current Waveform



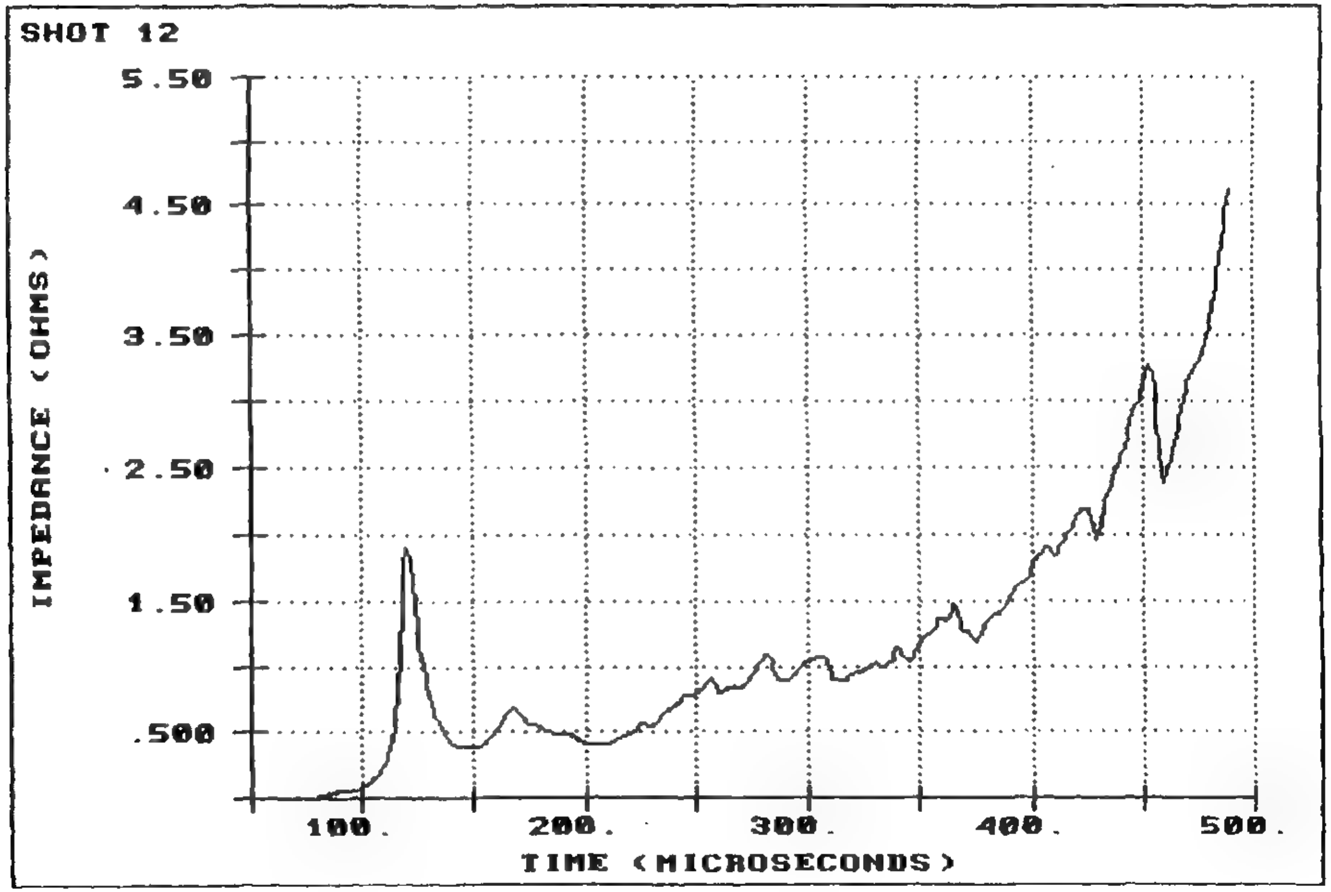
Los Alamos

Load Electrical Power



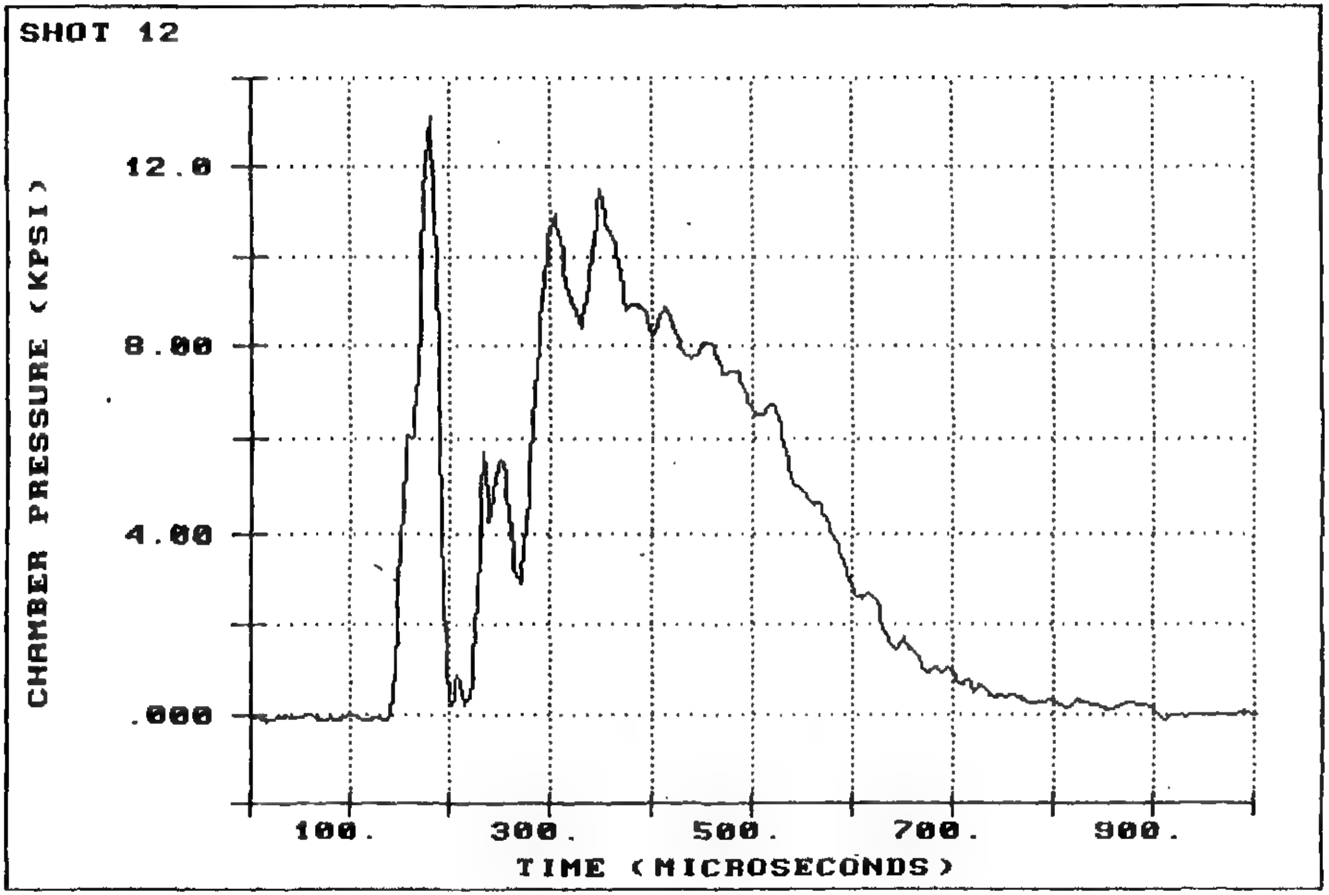
Los Alamos

Load Resistance



Los Alamos

Chamber Pressure

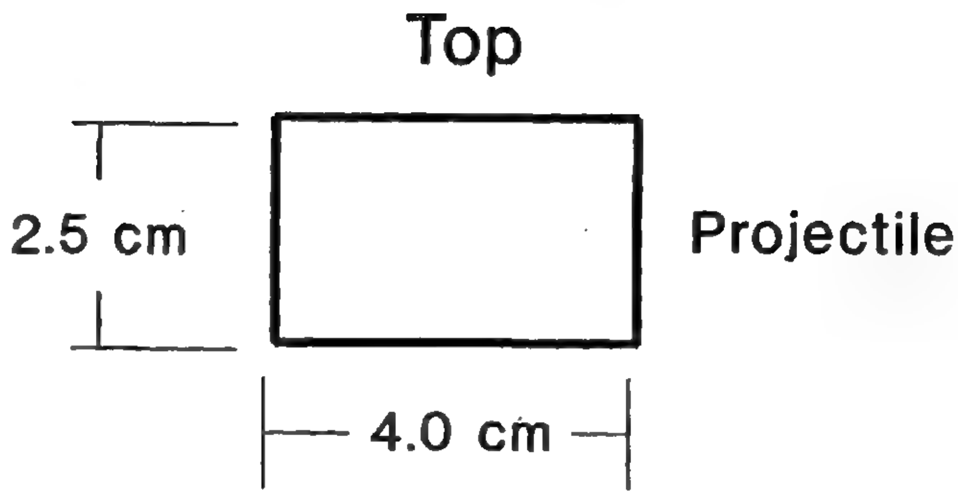


Los Alamos

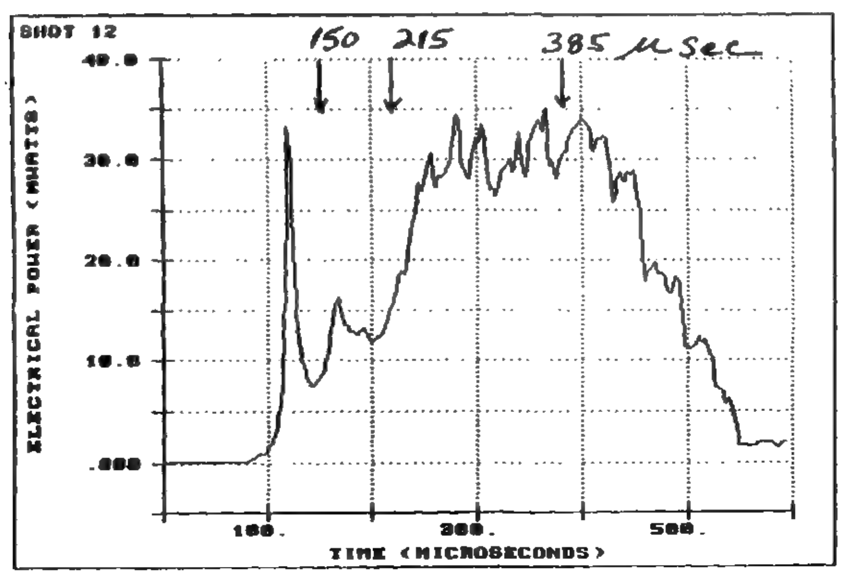
Radiographic Configuration

Copper Fiber-0.33 mm Diameter

Orientation

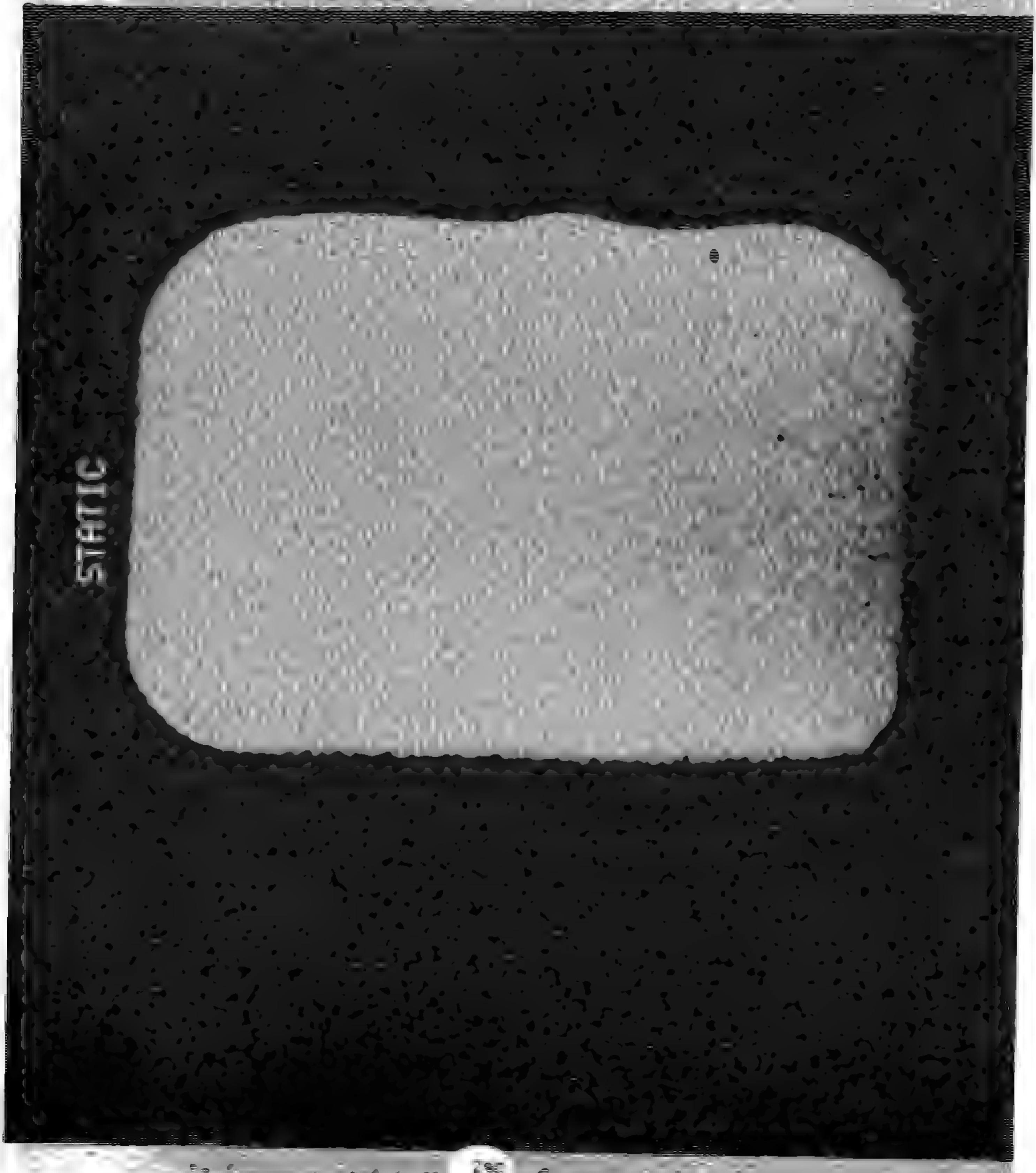


Time

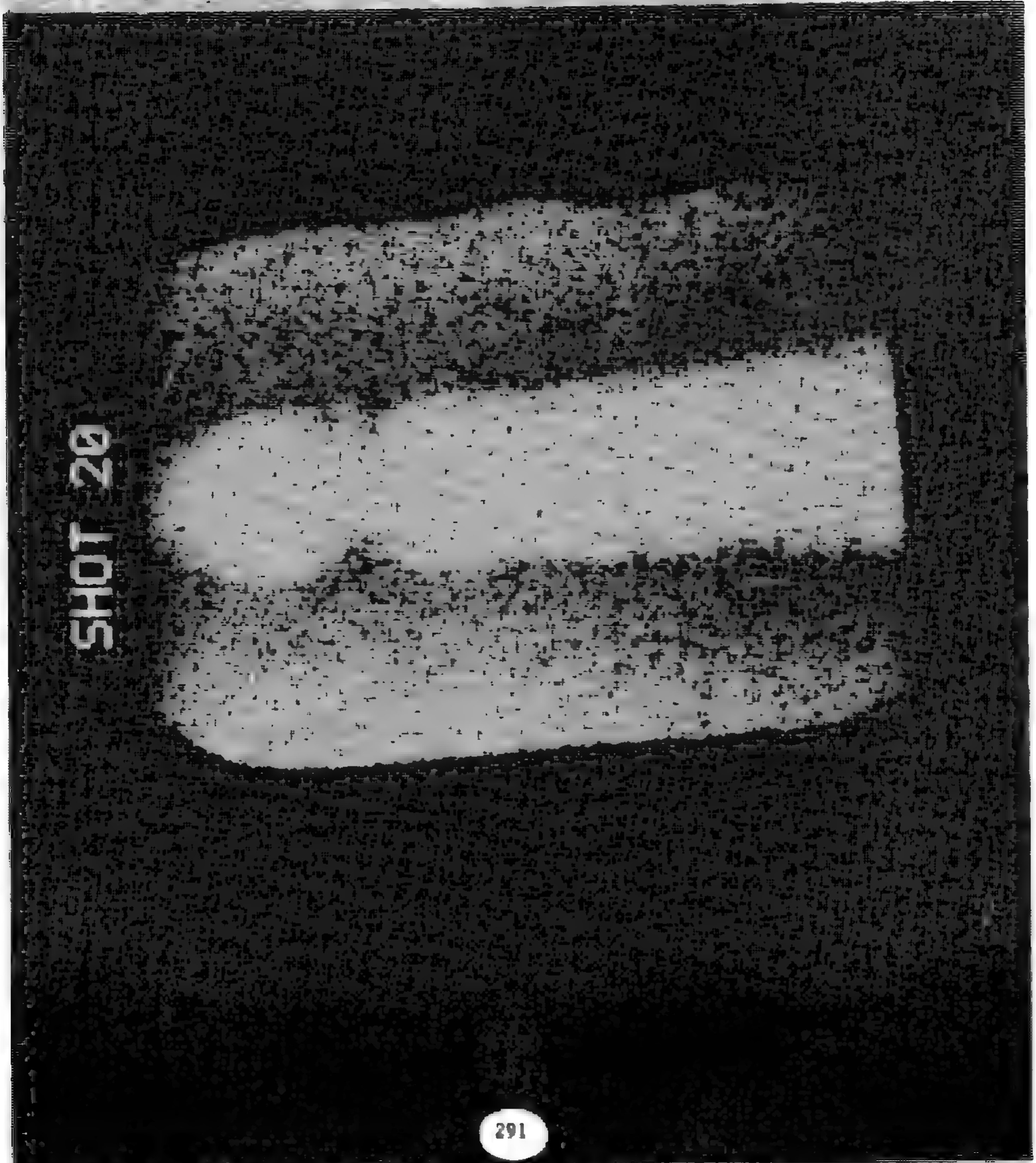


Los Alamos

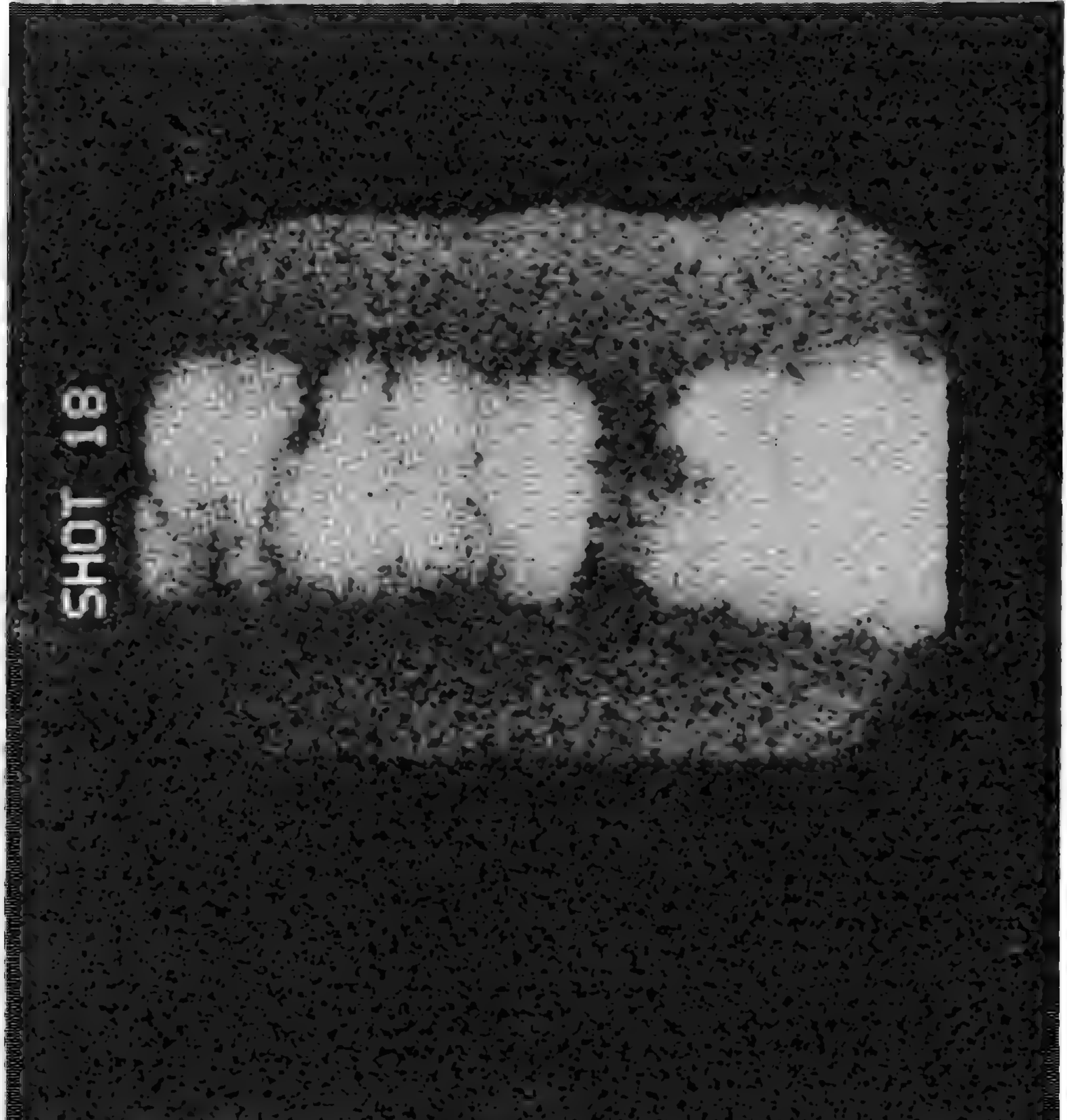
Static Chamber



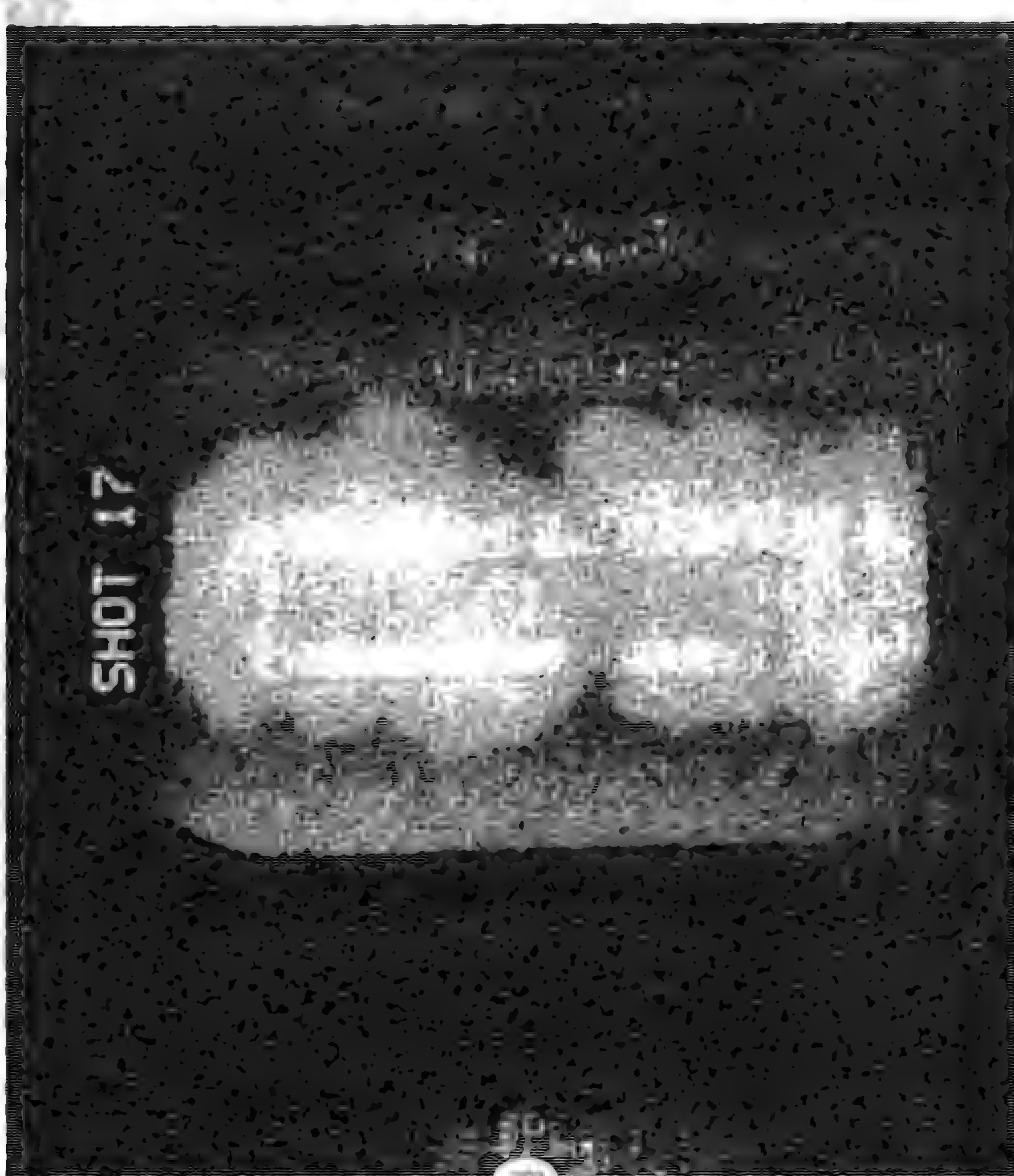
Copper - 150 microsec



Copper - 215 microsec



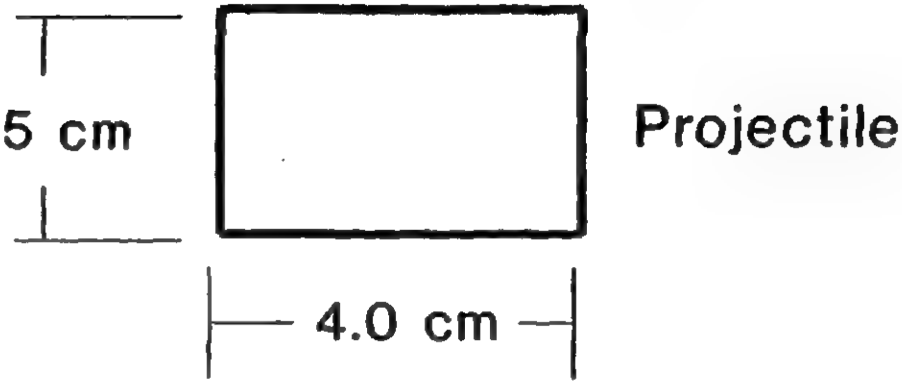
Copper - 385 microsec



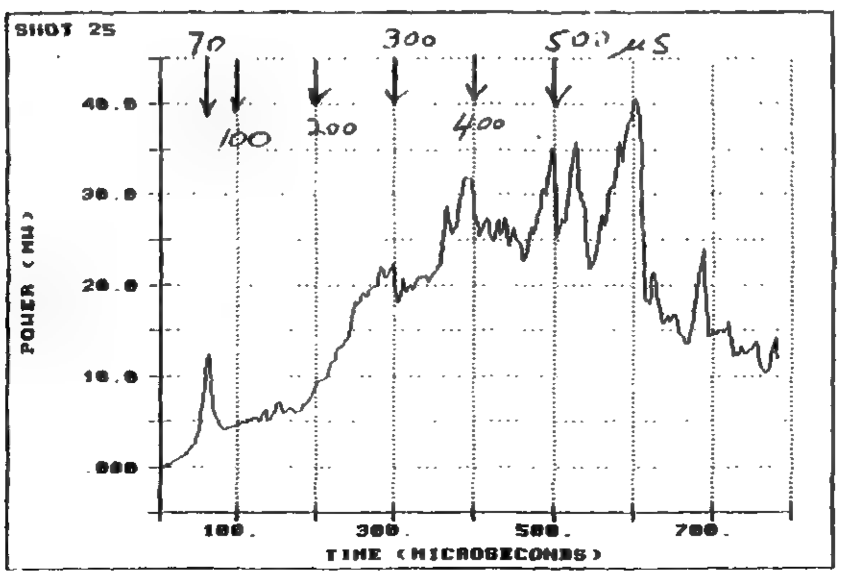
Radiographic Configuration
Carbon Fiber-0.5 mm Diameter

Orientation

Top

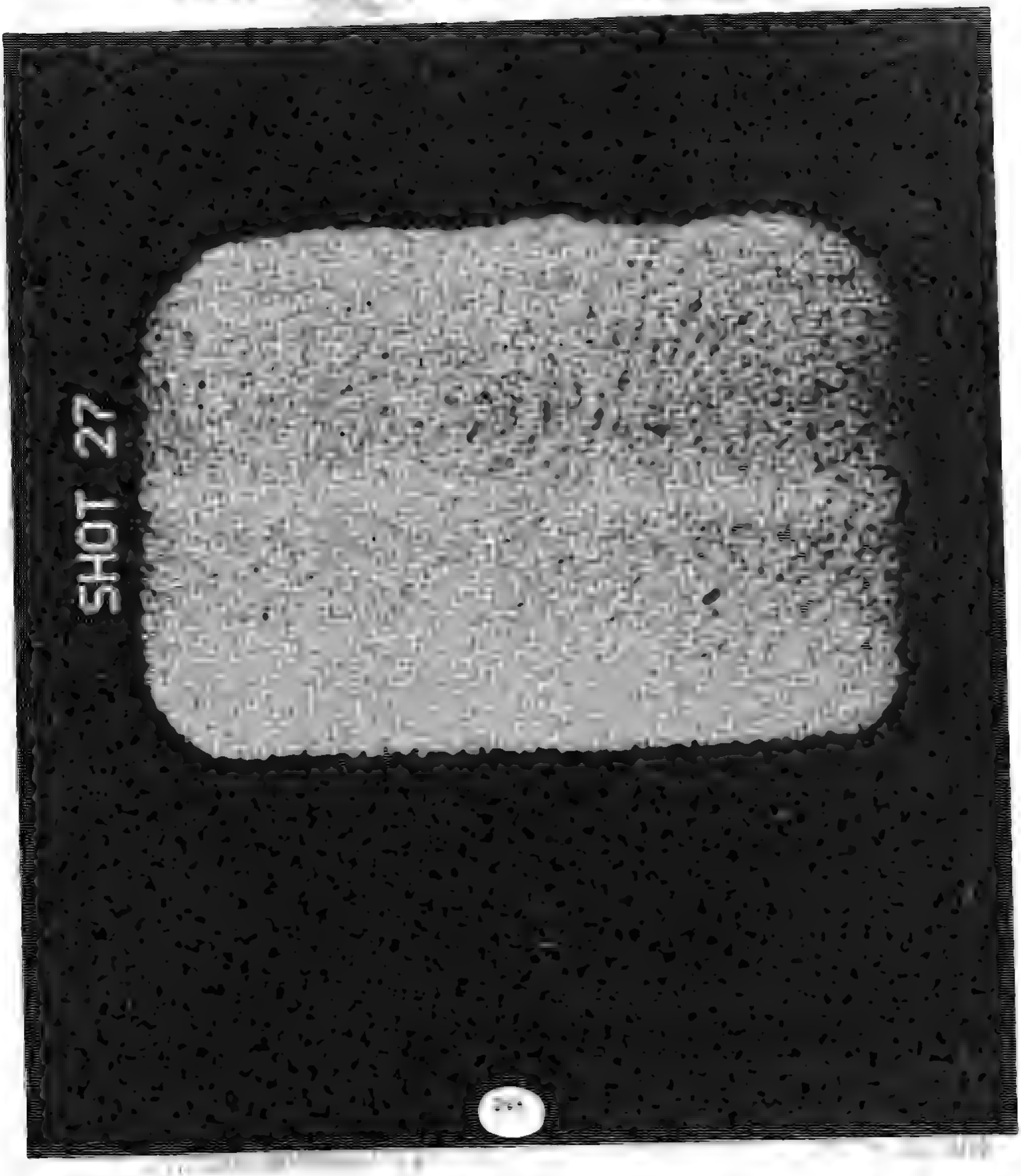


Time

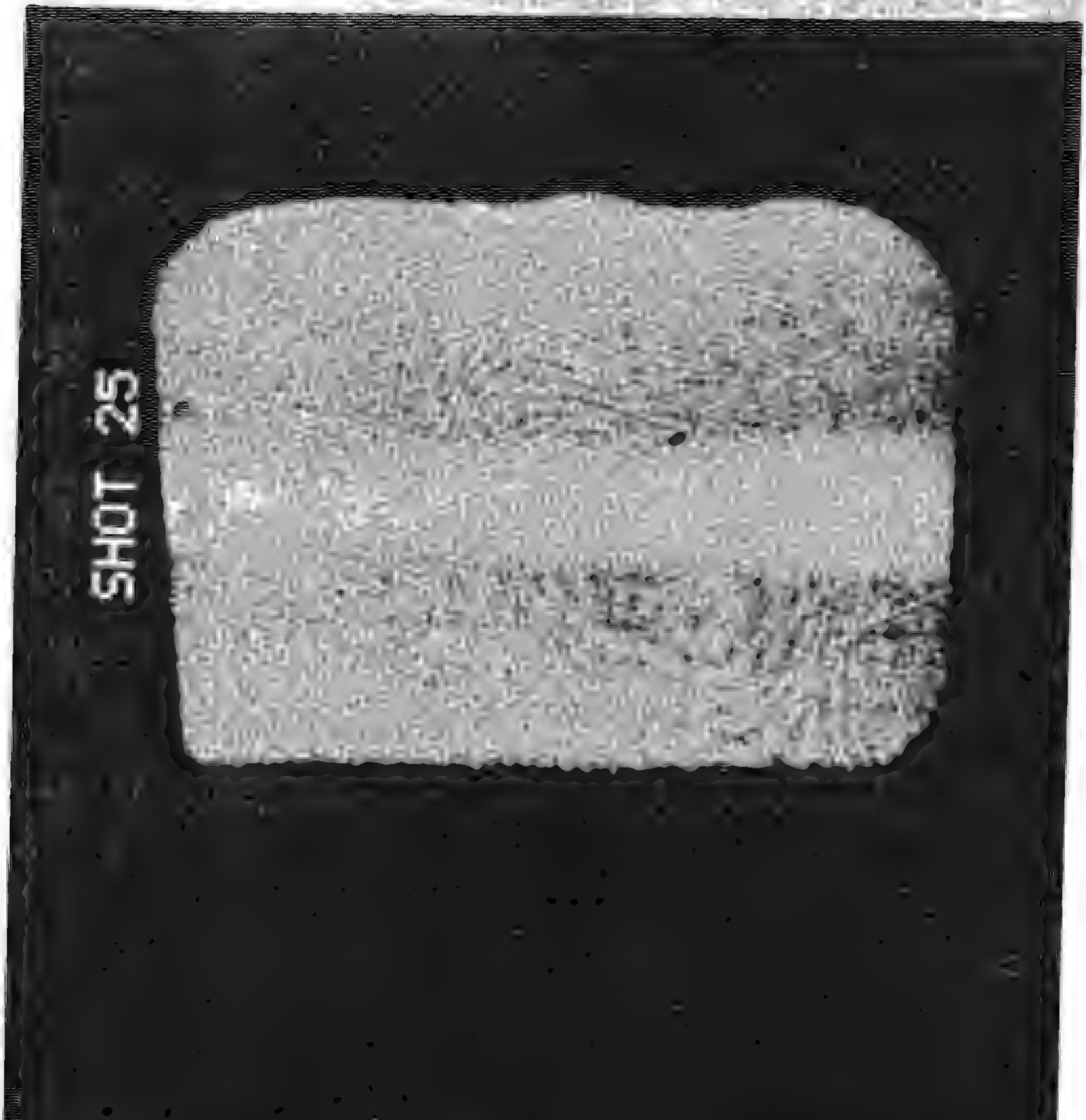


Los Alamos

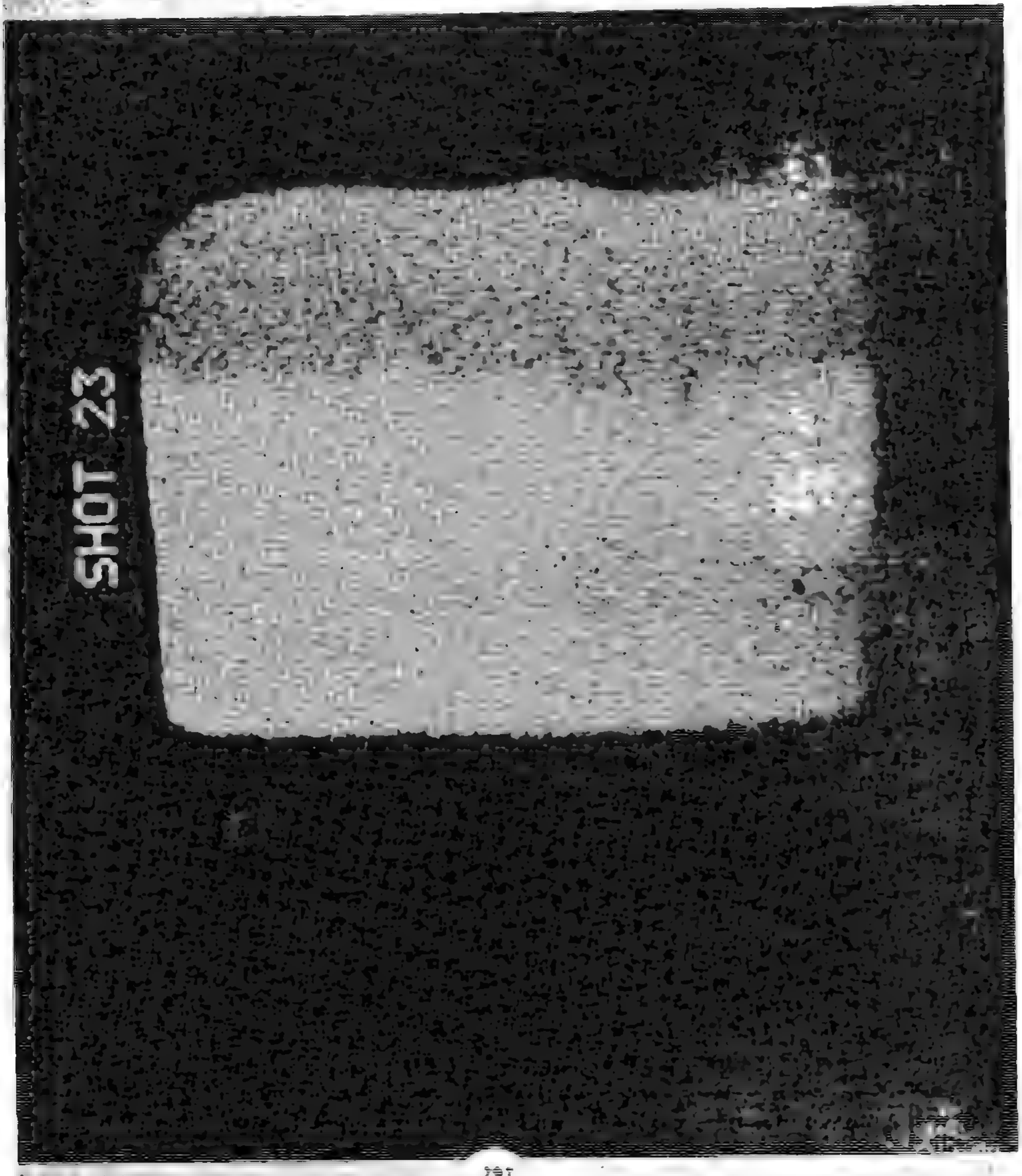
Carbon - 70 microsec



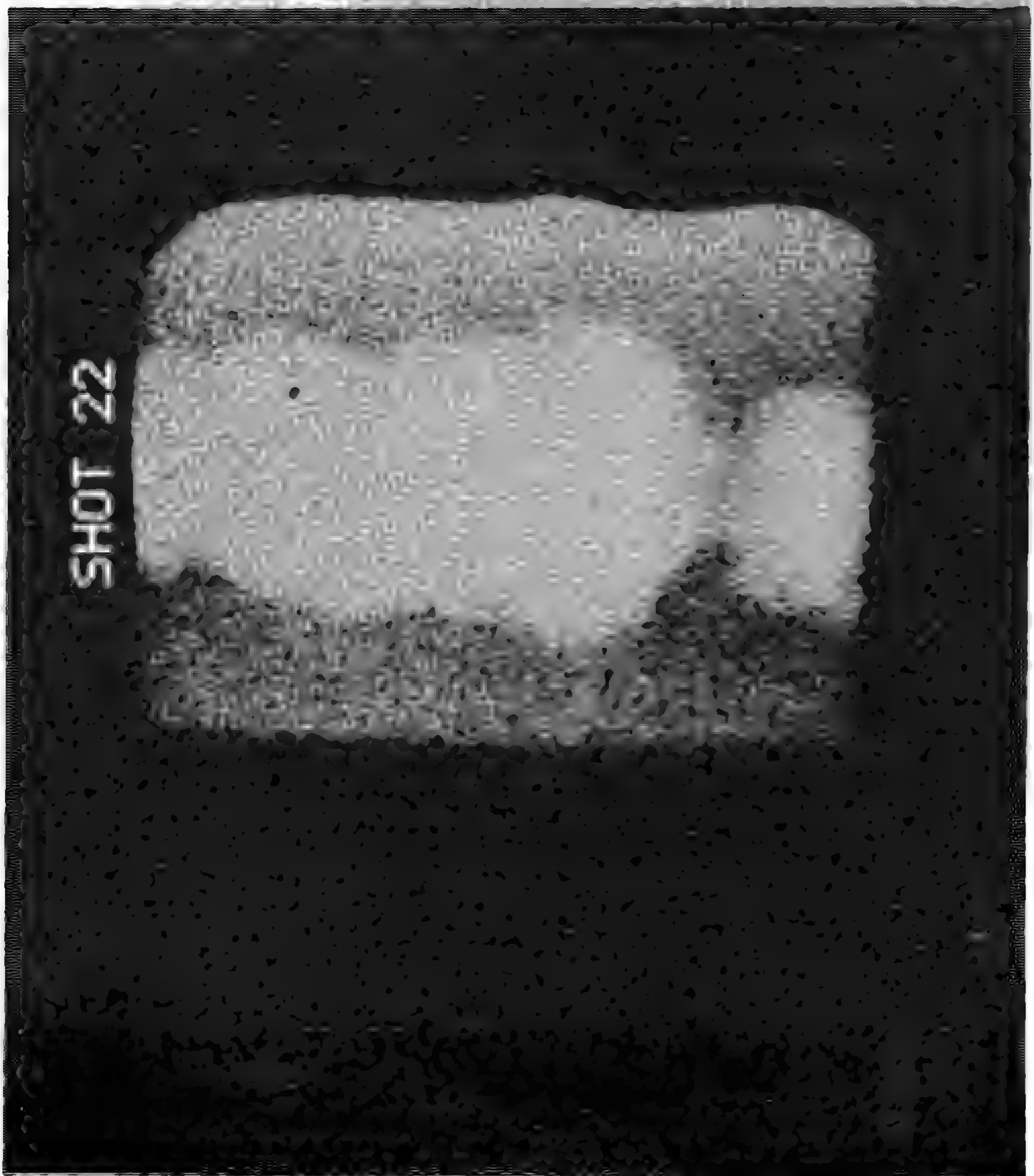
Carbon - 100 microsec



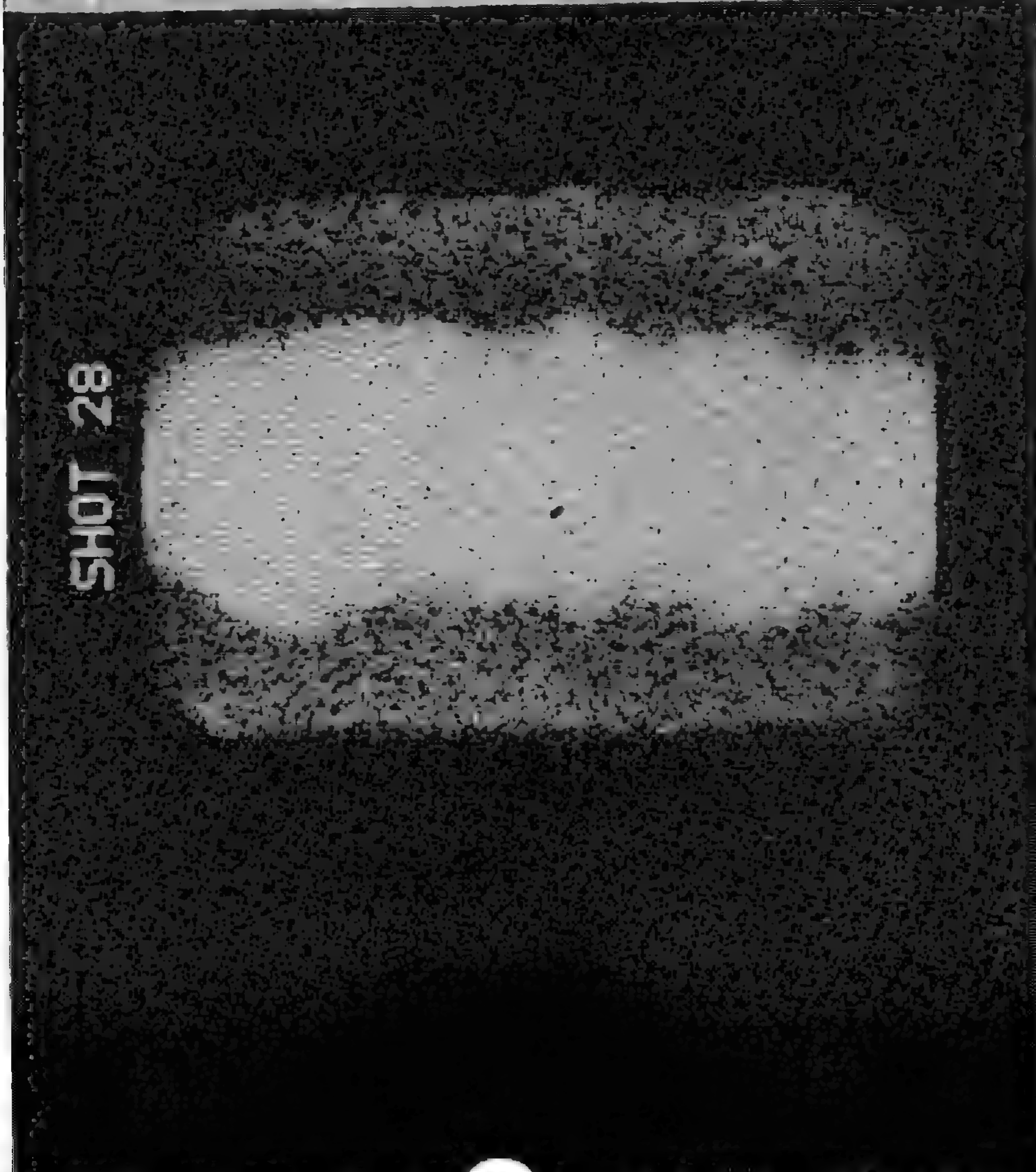
Carbon - 200 microsec



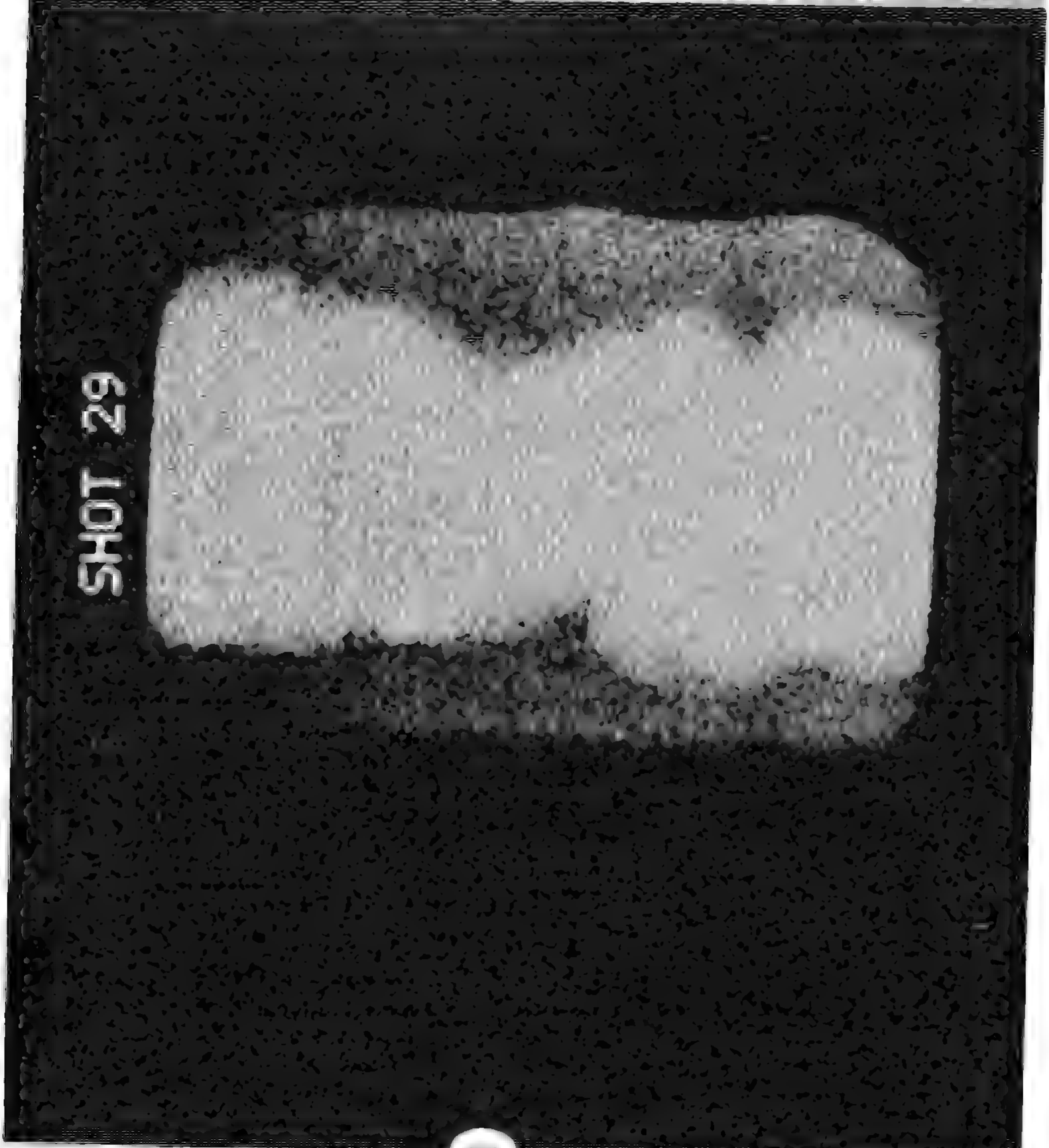
Carbon 300 microsec



Carbon - 400 microsec



Carbon - 500 microsec



What is the Mechanism Driving A Large Scale Instability?

- Simulate discharge using simple heat source to replace plasma model:

$$\dot{e}\rho = A\, e^{-\alpha r^2} \left[1 + B \sin^2 (az) \right] \cos^4 (ct)$$

Gaussian radial deposition

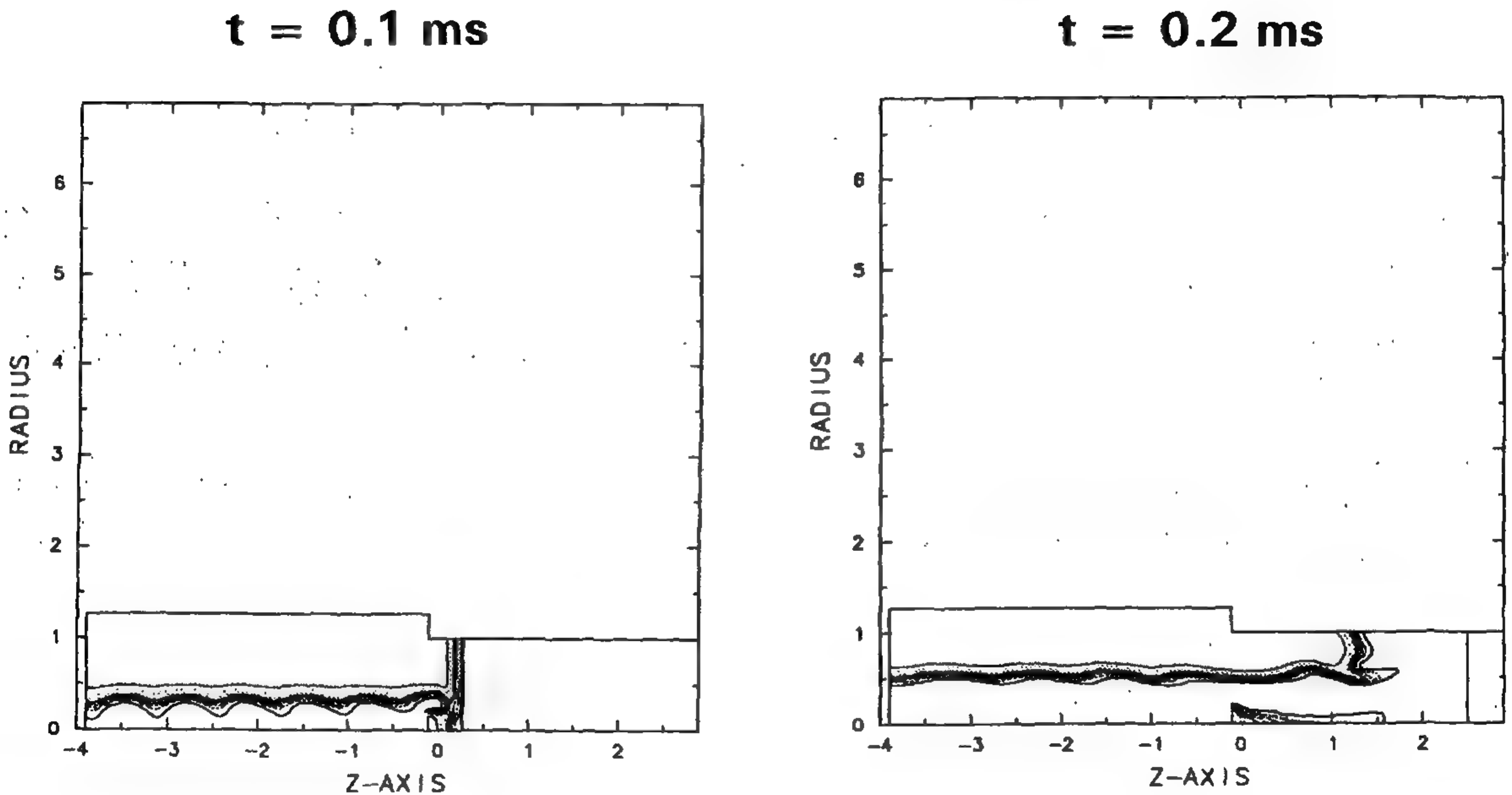
Periodic axial deposition

Time-dependent modulation

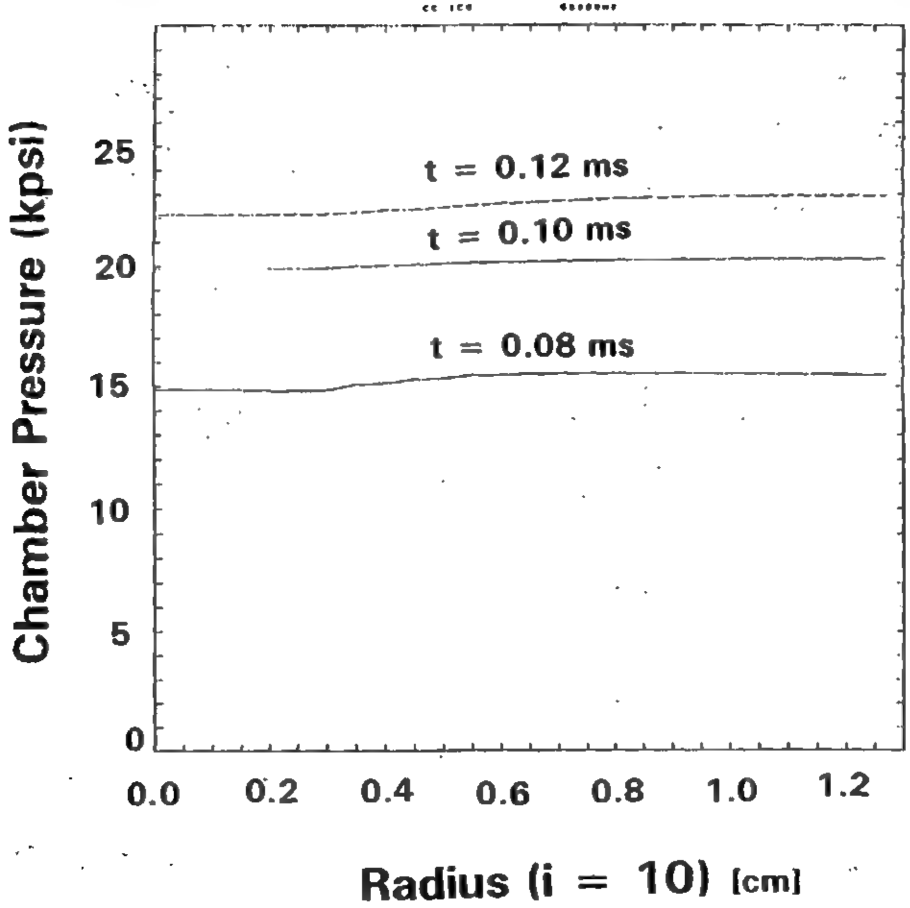
- Parameters chosen to match experiment. Amplitude chosen to give total power deposition of 20 kJ/ms.

Los Alamos

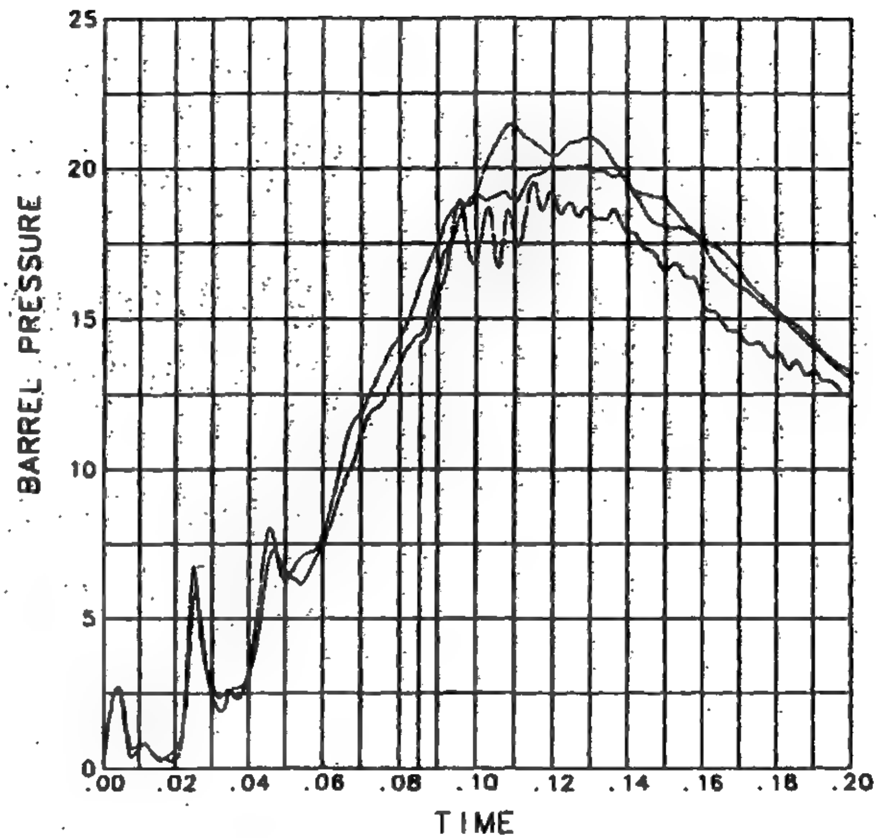
Perturbation Is Stabilized



Chamber Pressure vs. Radius at Different Times

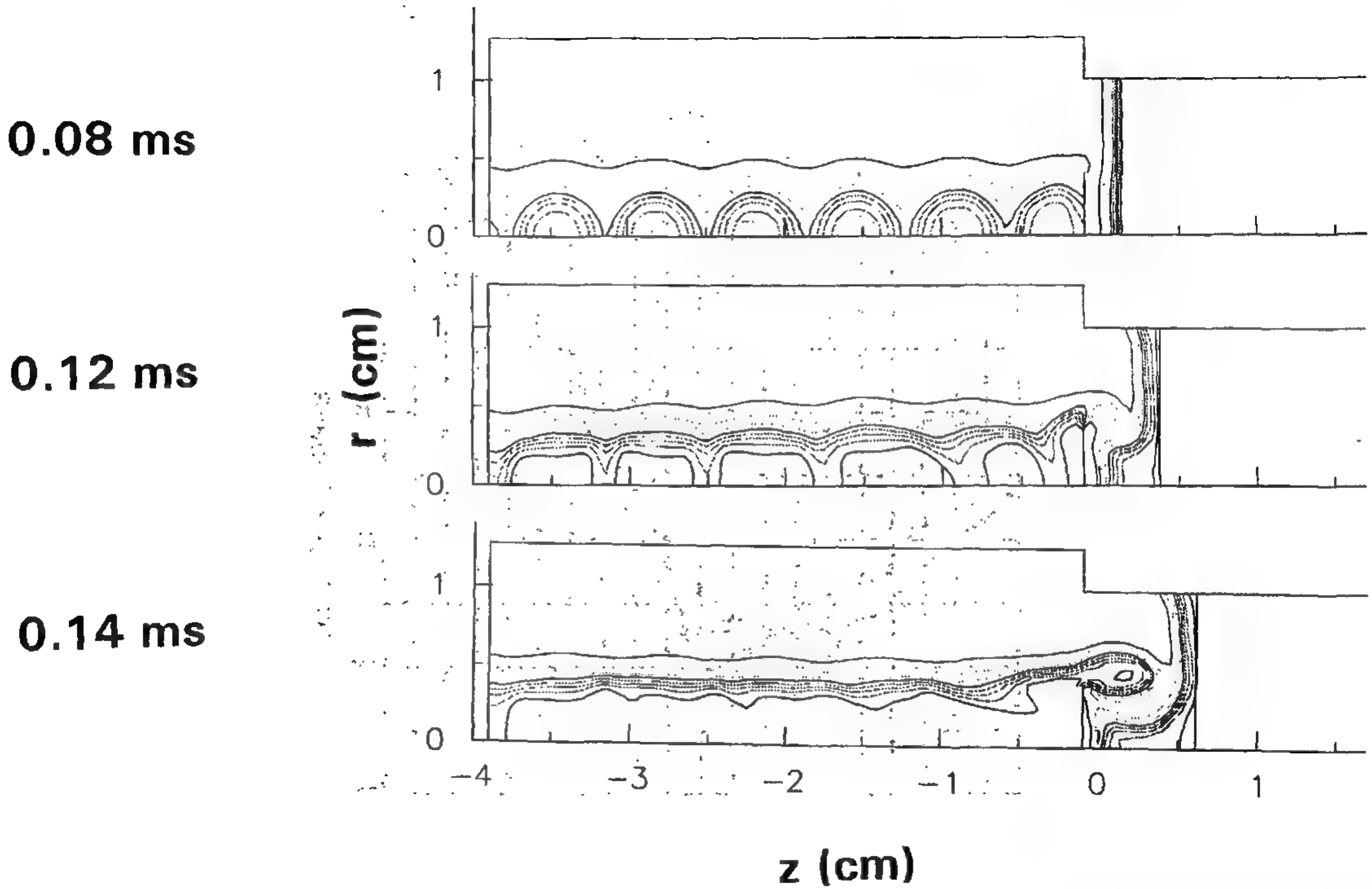


Chamber Pressure vs. Time

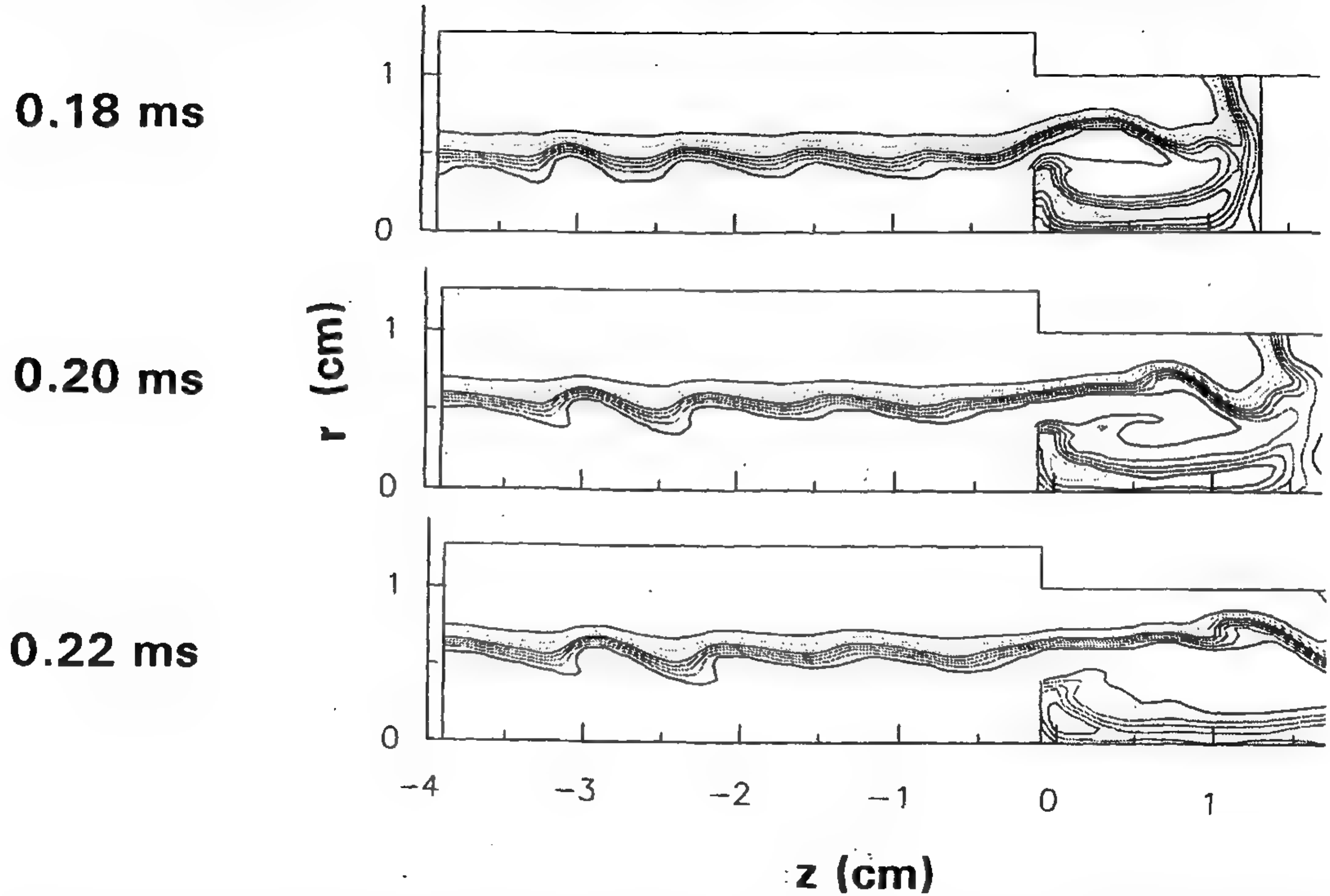


304

Perturbation Is Unstable With Time Modulation

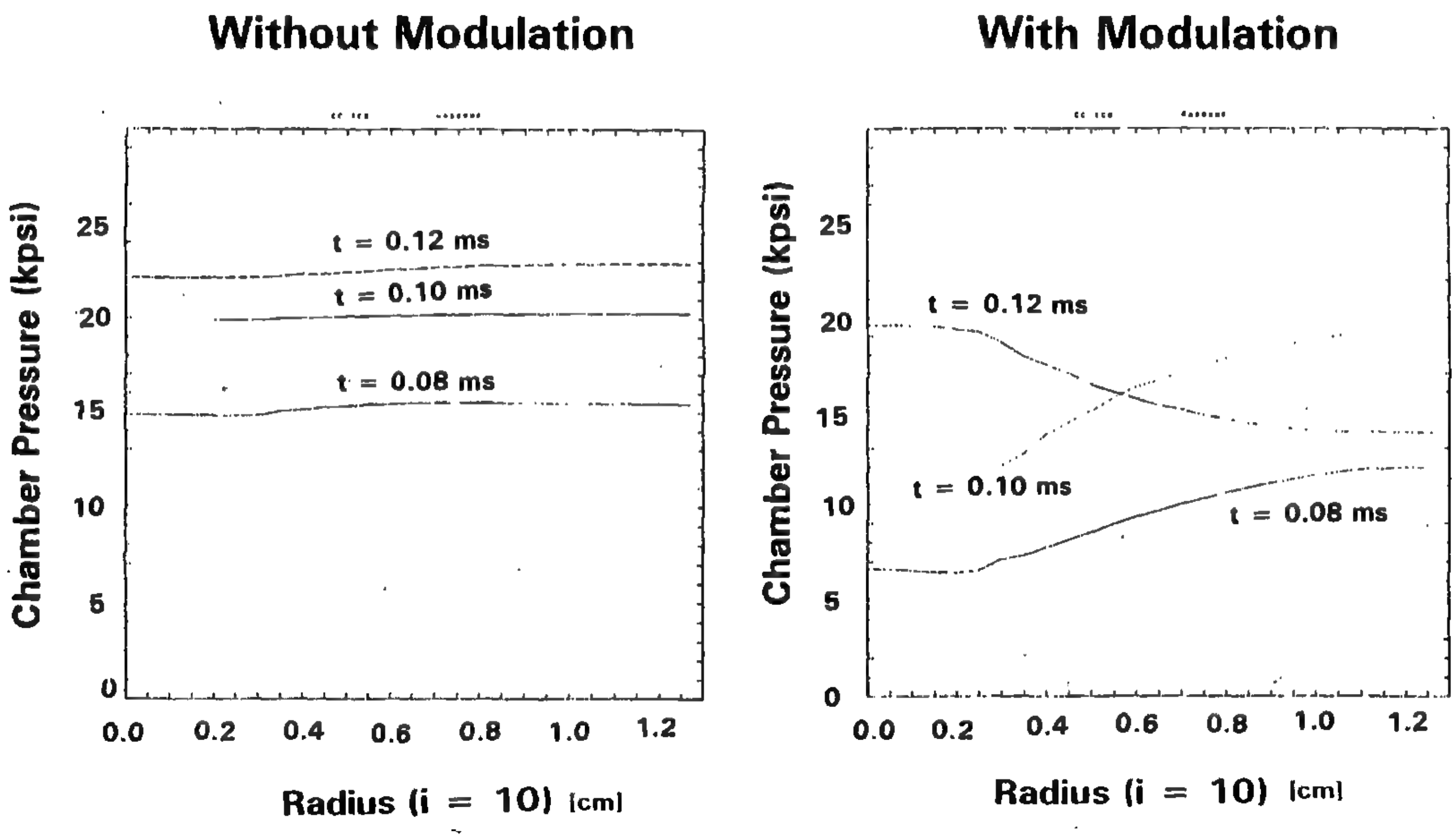


Perturbation Is Unstable With Time Modulation



Los Alamos

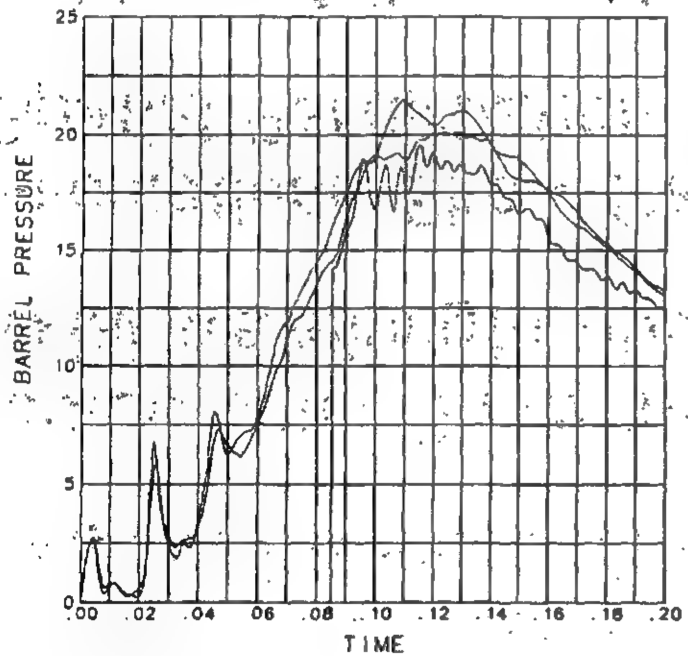
Chamber Pressure vs. Radius At Different Times



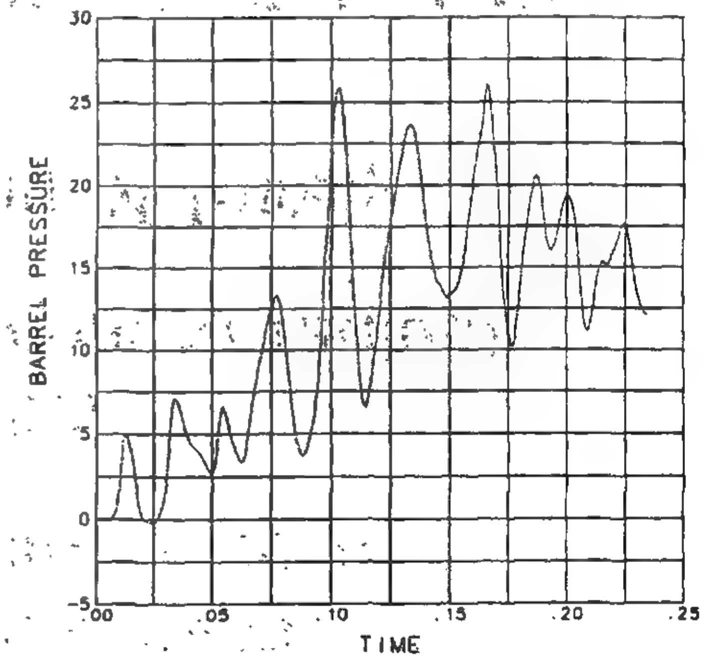
Los Alamos

Chamber Pressure vs. Time

Without modulation



With modulation



Summary

- Pressure and Electrical Measurements Suggest Pressure Waves are Important
- Radiographs Show Instability (axial wavelength about equal to radius)
- Calculations Show Damping of Purely Spatial Perturbation
- Addition of Power Modulation in Calculations (at Chamber Transit Period) Produces Instability

Los Alamos

Future Directions For ETC Computational Developmnet

- Incorporate detailed plasma dynamics
  - Sensitivity of conductivity to P and T
  - Can P waves be sustained by sensitivity of ohmic heating to pressure fluctuations?

- Couple circuit dynamics

- Examine potential of driving instabilities in propellants

- How can we avoid resonance between pressure waves and plasma dynamics? Begin examining different kinds of electrode configurations

Los Alamos

Future Experiments

- Study Different Configurations
  - ✓ Vary Geometry
  - ✓ Combustible Working Fluids
  - ✓ Vary Power Input

- Improve Measurements
  - ✓ Orthogonal X-Ray Views
  - ✓ Time Sequence on Single Shot
  - ✓ Time Resolved Photography
  - ✓ Time and Spatially Resolved Spectroscopy

Los Alamos

INTENTIONALLY LEFT BLANK.

ELECTROTHERMAL-CHEMICAL GUN MODELING

David W. King, Olin Rocket Research
and
Hugh McElroy, Olin Ordnance

ABSTRACT

A presentation will be made describing the nature of ET-C Gun Modeling. The key physics regarding combustion and arc physics will be discussed with regard to implementing a 2-D CFD model of the gun. At OLIN, both liquid and solid propellant 2-D modelling technology is being developed. The status of liquid propellant model will be presented along with example calculations.

ELECTROTHERMAL-CHEMICAL GUN MODELING

HUGH A. McEIROY
OLIN ORDINANCE

DAVID Q. KING
ROCKET RESEARCH COMPANY
OLIN DEFENSE SYSTEMS GROUP

JULY 11, 1991

ET-C CODES AND APPLICATIONS

0-D Codes	**EQUATION OF STATE FOR HIGH PRESSURE CHEMICAL EQUILIBRIUM** HUNTER & BLAKE give Impetus, γ BKW gives Curve Fit $\gamma(P,T)$	• USED FOR INTIAL PROPELLANT SCREENING • PROVIDES IMPETUS AND FLAME TEMPERATURE
1-D Codes	XNOVA/KTC γ = fixed	• MANY APPROXIMATIONS • γ = FIXED INCONSISTANT WITH ET-C PROPELLANTS
	XNOVA/KTC REAL GAS $\gamma(P,T)$	• AWAITING TEST
2-D Codes with Circuit Simulation	2D/L LIQUID PROPELLANT 2D/S SOLID PROPELLANT	• STEAM GUN SIMULATIONS AGREE WITH TEST • BURN RATE MODEL IS CRITICAL • INITIAL OPERATION 5/13/9 • PACKED BED MULTIFLUID

KEY PHYSICS ISSUES IN ETC MODELING

- 1D, QUASI 1D, 2D
  - 1D MODELS OR QUASI 1D REGIONS HAVE INFINITE SOUND SPEED IN RADIAL DIRECTION, FINITE IN AXIAL DIRECTION
  - PECULIAR EFFECTS ARE OBTAINED IN RADIAL DIRECTION AT INTERFACE OF 1D TO 2D REGION
- 2D MODEL CAN REPRESENT RADIAL VARIATION, WHICH PLAY A ROLE IN HIGH FREQUENCY PRESSURE WAVES

EQUATION OF STATE

- REAL GAS IN EQUILIBRIUM
- MULTIPHASE

317

ELECTROTHERMAL-CHEMICAL GUN MODELING

COMBUSTION

- GAS PHASE IN CHEMICAL EQUILIBRIUM
  - KINETIC RATES VERY HIGH AT HIGH PRESSURE
- EVOLUTION OF SOLID OR LIQUID TO GAS PHASE CONTROLS COMBUSTION RATE
  - DETAILED PROCESS INVOLVES DIFFUSION OF HEAT AND SPECIES
  - CAN BE CHARACTERIZED BY A TIME OR LENGTH SCALE TYPICALLY MUCH SMALLER THAN DIMENSIONS OF COMPUTATIONAL CONTROL VOLUME
  - SURFACE AREA DEPENDENT
- REPRESENTATIONS IN A COMPUTATIONAL CONTROL VOLUME
  - VOLUME AT P,T CONTAINS UNBURNED AND BURNED PROPELLANT
  - BURN RATE GIVEN BY EXPERIMENTAL PRESSURE OR TEMPERATURE CRITERION
  - MASS AND HEAT TRANSPORT ACROSS CONTROL VOLUME SURFACES STRONGLY AFFECT COMBUSTION INSIDE CONTROL VOLUME
- MASS AND ENERGY TRANSPORT GOVERNED BY MIXING LENGTH TURBULENCE MODEL

ARC HEAT INPUT

- KILOAMP DISCHARGE AT KILOBAR PRESSURES HAVE VERY SMALL RADIUS
  - RADIUS GIVEN BY PRESSURE AND ENERGY BALANCE ACROSS ARC TO FLUID BOUNDARY
  - TYPICAL $R < 0.5$ mm
- VERY SMALL VOLUME OF FLUID IS IONIZED
- INTENSE RADIATION FROM ARC IS TRAPPED IN VERY SMALL DISTANCE
- IONIZED FLUID RECOMBINES RAPIDLY AT KILOBAR PRESSURES
- EXPECT VERY LITTLE EFFECT ON CHEMISTRY FROM IONS
- TREAT ARC AS LOCALIZED HEAT SOURCE

ELECTROTHERMAL-CHEMICAL GUN MODELING

STATUS

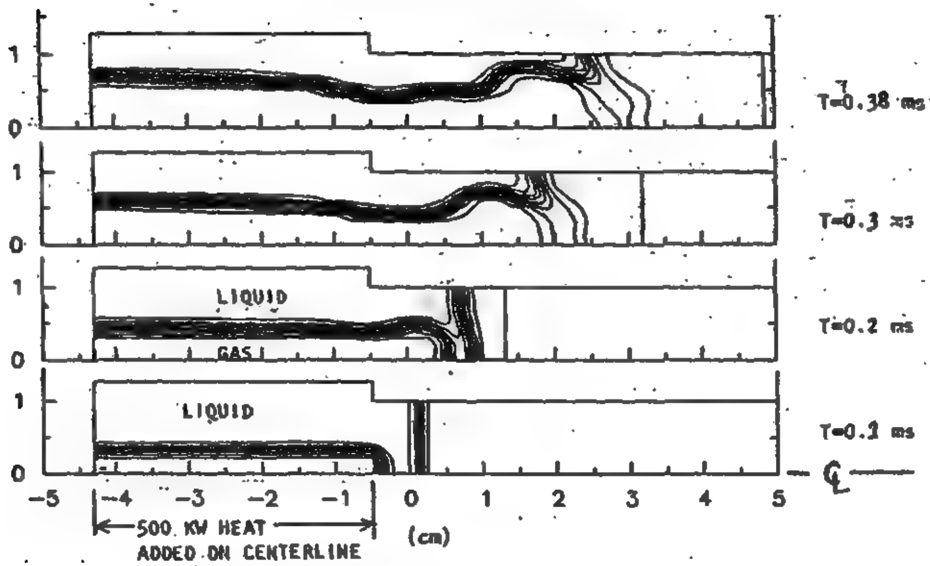
- **APPROACH**
  - 2D CODES DEVELOPED BY LOS ALAMOS NATIONAL LABORATORIES UNDER CONTRACT TO ROCKET RESEARCH COMPANY/OLIN DEFENSE SYSTEMS GROUP
  - IN HOUSE MODIFICATION FOR SPECIFIC APPLICATIONS
- **LIQUID PROPELLANT 2D MODEL**
  - OPERATIONAL
  - MULTIPHASE, SINGLE VELOCITY & TEMPERATURE
  - VALIDATION WITH EXOTHERMIC PROPELLANTS UNDERWAY

STATUS (CONTINUED)

- SOLID PROPELLANT 2D MODEL
  - READY FOR INITIAL TESTING
  - MULTIFLUID - SEPARATE TEMPERATURES & VELOCITIES FOR GAS AND SOLID FLUIDS
  - HANDLES SOLID PROPELLANT AND FRACTURED PIECES OR "RUBBLE" WITH CLOSE PACKED BED

ELECTROTHERMAL-CHEMICAL GUN MODELING

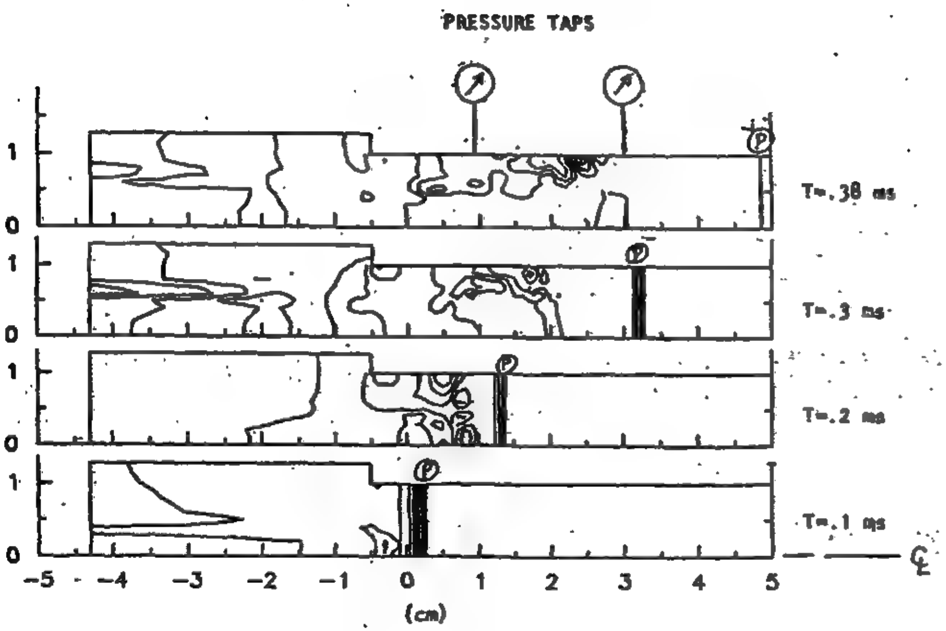
EXAMPLE CALCULATION - STEAM GUN WITH CENTERLINE HEATING
DENSITY CONTOURS

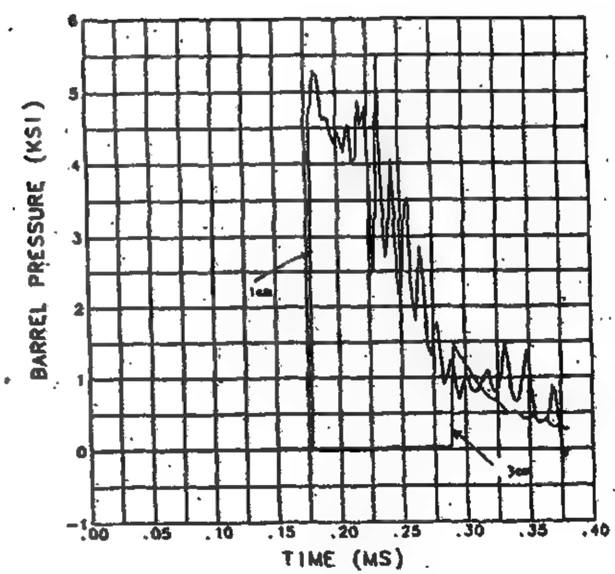


Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP

ELECTROTHERMAL-CHEMICAL GUN MODELING

EXAMPLE CALCULATION - STEAM GUN WITH CENTERLINE HEATING PRESSURE CONTOURS





323

APPLICATIONS

- GAS GENERATORS
- ET-C MODELING
  - VARIOUS GEOMETRIES
  - ALTERNATE ELECTRODE CONFIGURATIONS

CONCLUSIONS

- LIQUID & SOLID PROPELLANT MODELS ARE OPERATIONAL AND VALIDATION IS UNDERWAY
- APPROACH YEILDS A CAPABILITY THAT IS EASILY ADAPTED TO PROBLEM SPECIFIC SPECIALIZATIONS

INTENTIONALLY LEFT BLANK.

RAILGUN RESEARCH RELEVANT TO ELECTROTHERMAL GUNS

Jad H. Batteh
Science Applications International Corporation
Marietta, GA 30062

ABSTRACT

Some aspects of the modeling and diagnostics of electrothermal guns are common to railguns, as well. The objective of this presentation is to compare and contrast the two technologies and to provide a reference guide to the recent relevant literature describing railgun research. Particular emphasis is placed on the following areas - the calculation of thermodynamic and transport properties in very dense, relatively low temperature plasma; on-board projectile diagnostics; spectroscopic analysis; and the confinement and stability of high-pressure arc discharges.

Railgun Research Relevant to Electrothermal Guns

Jad H. Batteh
Science Applications International Corporation
1519 Johnson Ferry Road
Suite 300
Marietta, Georgia 30062
(404)973-8935

Presented at JANNAF Workshop on
ETC Modeling and Diagnostics
July 9 - 11, 1991
Aberdeen Proving Ground, MD

Objective

- Review railgun research relevant to ETC technology
  - Analysis of plasma jets
  - Diagnostics
- Provide references to the relevant literature

SAIC
An Employee Owned Company

Basic References for Railgun Physics

- Proceedings of the Symposia on Electromagnetic Launcher Technology published by IEEE Transactions on Magnetics

  1. Vol. 18, January 1982
  2. Vol. 20, March 1984
  3. Vol. 22, November 1986
  4. Vol. 25, January 1989
  5. Vol. 27, January 1991

- Special Issue on Electromagnetic Launchers, IEEE Transactions on Plasma Science. Vol. 17, June 1989.

- "Proceedings of the Electromagnetic Launcher Workshop II - Diagnostic Techniques", AFATL-TR-87-65, January 1988.

SAIC.
An Employee Owned Company

Comparison of Plasma Flows

	v(km/s)	P(atm)	T(K)	β*	Length Scale (m)	Flow Character	Elect. Cond. (10^4 mhos/m)
MHD Generator	1	1	10^3	0.1	1 - 10	Channel	0.01 - 0.1
High-Speed Re-entry	1 - 10	≤ 1	10^3-10^4	∞	1 - 10	Free	0.01
MPD Thrusters	10	1 - 10	10^4	1	1 - 10	Channel	0.01
Plasma Armature	10	10^3	10^4	1	0.1	Slug	1
ETC Plasma	10	10^3	10^4	10	0.1	Channel	1

$$^*\beta = \frac{\text{thermodynamic pressure}}{\text{magnetic pressure}}$$

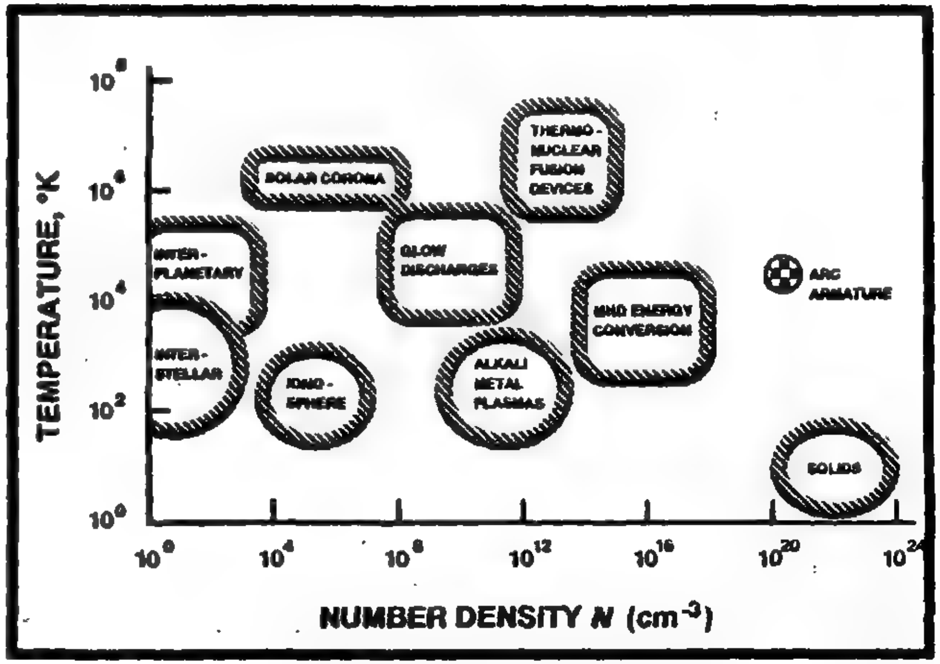
INCOMPLETE UNDERSTANDING LIMITS OUR ABILITY TO CONTROL ARMATURE PERFORMANCE

MODELING DIFFICULTIES

- MECHANISMS WHICH ARE CONTROL ARC MASS AND COMPOSITION ARE NOT WELL UNDERSTOOD
  - COMPLEX INITIATION PHYSICS
  - ARMATURE EXCHANGES MATERIAL WITH BORE THROUGH ABLATION AND PLATING
- CONVENTIONAL ELECTRIC AND THERMAL TRANSPORT MODELS ARE INADEQUATE (NONIDEALL PLASMA)
- PLASMA REPRESENTS A NON - STEADY, 3 - D, TURBULENT, POSSIBLY MULTI - PHASE MHD FLOW
- PLASMA MAY BE SUSCEPTIBLE TO INSTABILITIES

DIAGNOSTIC DIFFICULTIES

- LIMITED DIAGNOSTICS CURRENTLY AVAILABLE
- RELIABLE, HIGH FIDELITY, CONTINUOUS MEASUREMENTS OF ACCELERATION ARE UNAVAILABLE
- HIGH PRESSURES IMPEDE OPTICAL DIAGNOSTICS OF PLASMA CORE
- PRESENCE OF STRONG TRANSIENT FIELDS



SA90160J-5

PLASMA PARAMETERS

- NONIDEAL PARAMETER

$$\gamma \equiv \frac{\text{Colomb Energy}}{\text{Thermal Energy}} = \left[\left(\frac{4\pi}{9}\right)^{1/3} \frac{e^2}{4\pi\epsilon_o k}\right] \left[\frac{\alpha(1+z)}{(1+\alpha)^{2/3}}\right] \frac{n^{1/3}}{T}$$

- NUMBER OF PARTICLES IN A DEBYE SPHERE

$$N_D \;\alpha\; \left(\frac{1}{\gamma}\right)^{3/2}$$

- DEGENERACY TEMPERATURE RATIO

$$t_D = \frac{T_o}{T} = \left[\left(\frac{3}{4\pi}\right)^{2/3} \frac{h^2}{m_e\ k}\right] \alpha^{2/3} \frac{n^{2/3}}{T}$$

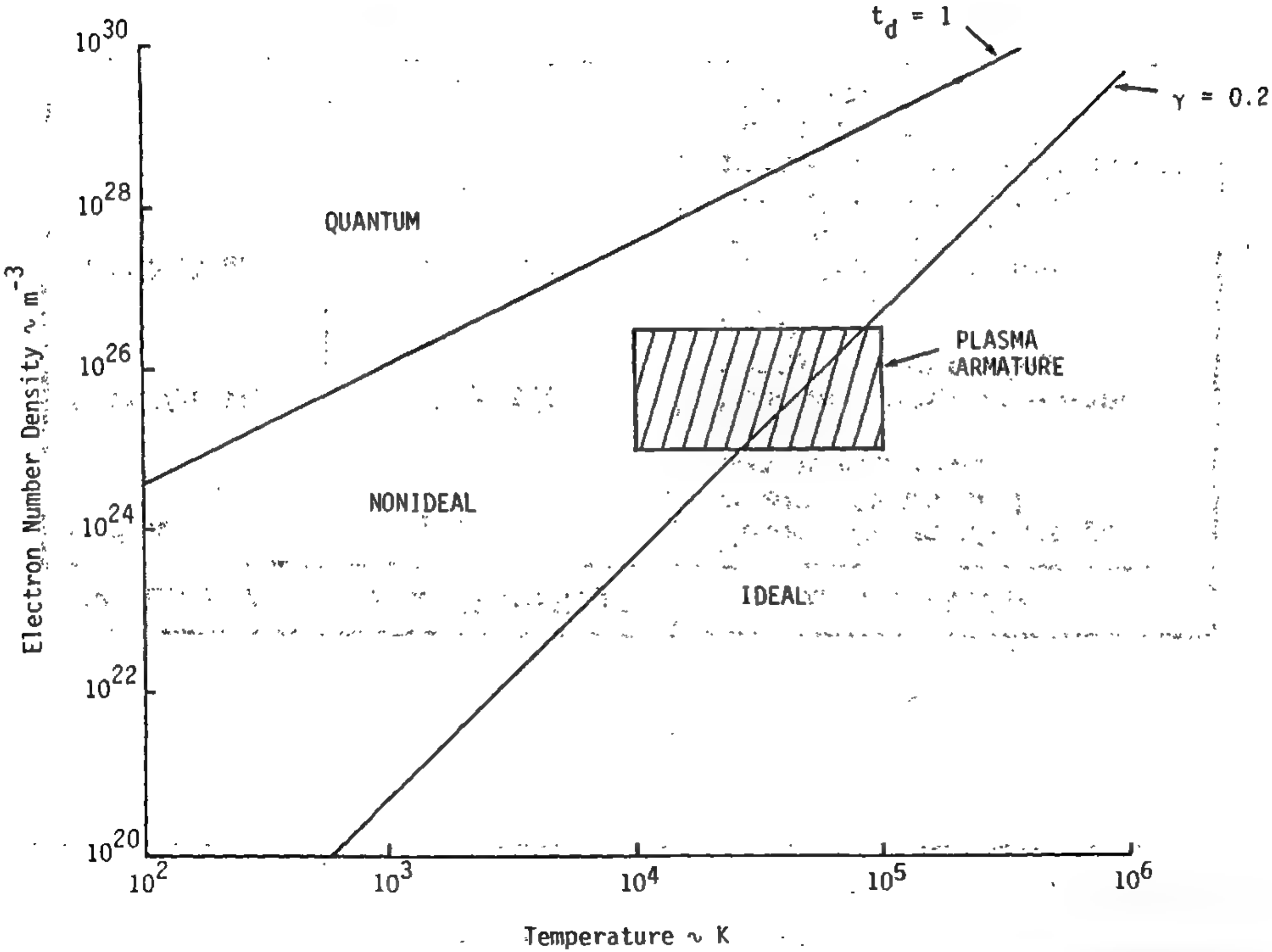
SAIC
Science Applications International Corporation

TYPES OF PLASMAS

CATEGORY	REQUIREMENT	IMPLICATION
IDEAL	$\gamma << 1$	Neglect Coulomb energy relative to thermal energy in plasma
NONIDEAL	$\gamma \gtrsim 0.2$	Must account for Coulomb energy in determining properties
QUANTUM	$t_D \gtrsim 1$	Free electrons no longer described by Boltzmann statistics, and plasma properties must be based on Fermi–Dirac quantum statistics

SAIC
Science Applications International Corporation

METAL–PLASMA ARMATURES ARE TYPICALLY NONIDEAL



Assumes Singly Ionized Plasma

SAIC Science Applications International Corporation

IMPACT OF NONIDEAL PLASMA BEHAVIOR

- SIGNIFICANT DECREASE IN THE PLASMA CONDUCTIVITY BELOW THAT PREDICTED BY SPITZER'S FORMULA
- LOWERING OF THE IONIZATION POTENTIAL
- DECREASE IN GAS PRESSURE WHEN COMPARED TO THE IDEAL GAS EQUATION OF STATE

SAIC
Science Applications International Corporation

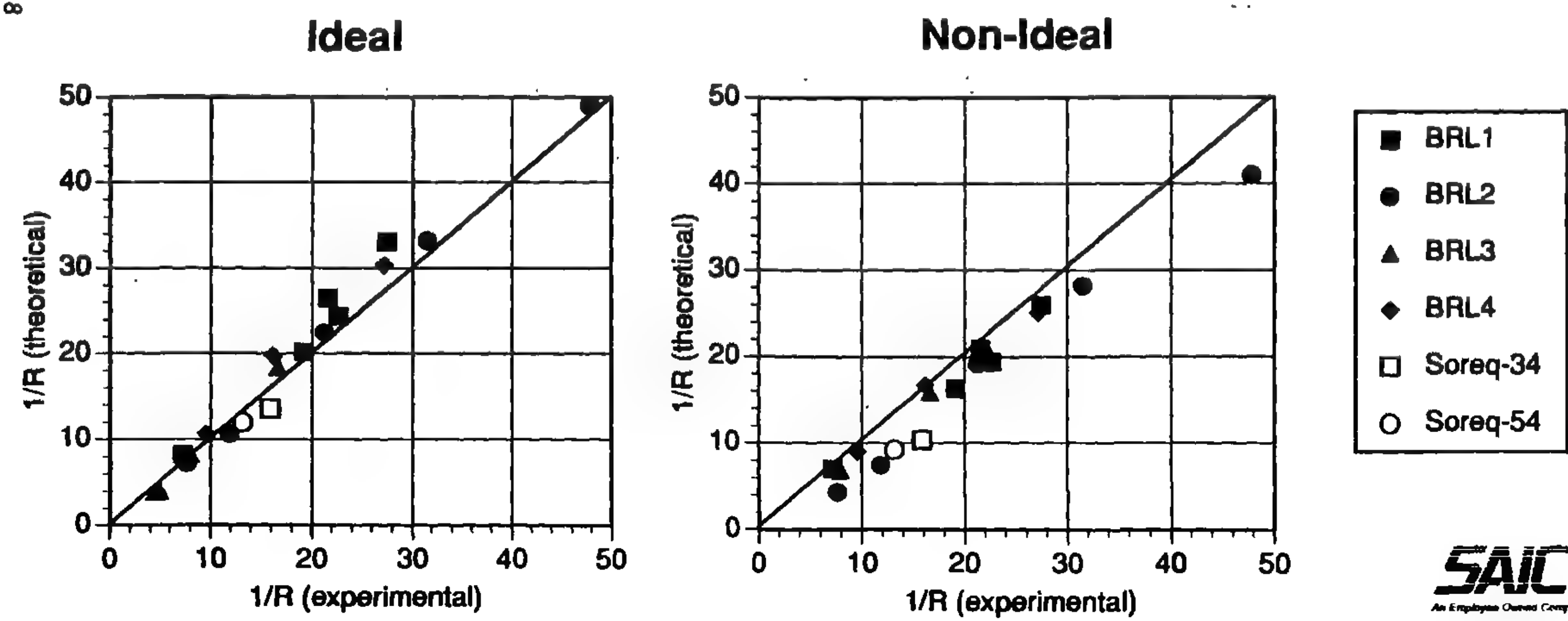
Selected References for Nonideal Plasma Properties

- "Electrical Conductivity of Nonideal Quasi - Metallic Plasmas," A.H. Khalfaoui, IEEE Trans. on Plasma Science *PS-12*, 179 (1984)
- "The Electrical Conductivity of Plasma in a Wide Range of Charge Densities," Yu. K. Kurilenkov and A.A. Valuev, Beitr. Plasma phys. *24*, 161 (1984).
- "Physical Properties of High-Pressure Plasmas of Hydrogen and Copper in the Temperature Regime 5000 - 60000 K, "P. Kovitya, IEEE Trans. on Plasma Science *PS-13*, 587 (1985).
- "Electrical Conductivity of Nonideal Plasmas," R.J. Zollweg and R.W. Liebermann, J. Appl. Phys. *62*, 3621 (1987).
- "Thermodynamic and Electrical Properties of Railgun Plasma Armatures," G.E. Rolader and J.H. Batteh, IEEE Trans. on Plasma Science *17*, 439 (1989)
- "Electrical Conductivity and Thermodynamic Functions of Weekly Nonideal Plasma," R.B. Mohanti and J.G. Gilligan, J. Appl. Phys. *68*, 5044 (1990).

SAIC.
An Employee Owned Company

Comparison of Measured and Predicted Conductance for Plasma Capillaries

- Based on quasi-steady model of Powell (in Technology Efforts in ET Gun Propulsion, Vol. 2, 1989)
- Predictions assume choked flow
- Measured values denote conductance in units of mhos
- Non-ideal model based on Kurilenkov and Valuev



SAIC
An Employee Owned Company

Factors That Influence Current Distributions in Confined and Unconfined Discharges

339

- Solid boundaries
  - railgun bore
  - capillary wall

- Dynamic (pressure) equilibrium
  - discharge into liquid

- Electric field distribution

- Conductivity distribution

- Flowfield

$$J = \sigma (E + V \times B)$$

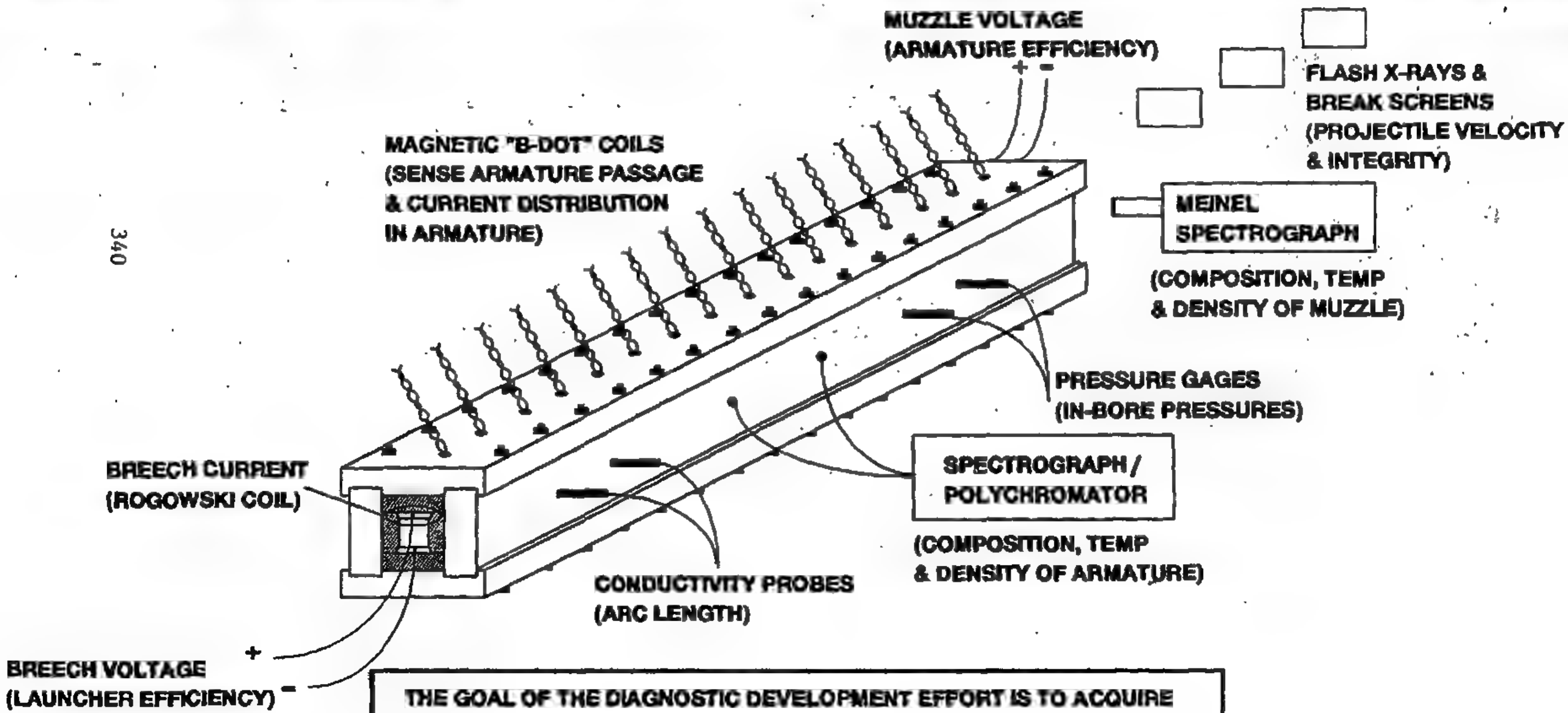
- Magnetic confinement

  - $\beta \leq 1$

- Instabilities

SAIC
An Employee Owned Company

HRP PHASE I
DIAGNOSTIC DEVELOPMENT



THE GOAL OF THE DIAGNOSTIC DEVELOPMENT EFFORT IS TO ACQUIRE THE NECESSARY RAW INFORMATION THAT CAN BE USED TO DETERMINE COMPONENT CHARACTERISTICS AND EML PERFORMANCE

IA90151B-18

Overview of Advanced Railgun Diagnostics

Diagnostics	Measured or Inferred Parameters	Issues	Selected References
Spectroscopy of plasma armatures	• Composition • Temperature • Flow Structure	• Short optical depths • Data interpretation transient • Coating/shielding	Keefer, et al. - Ref. 1, p 217 - Ref. 2, p. 295 - Ref. 3, p. 360 Clothiaux, et al. - Ref. 1, p. 199
X-ray absorption of plasma armature	• Density • Composition	• Initial estimate of components	Clothiaux, et al. - Ref. 1, p. 139 - Ref. 1, p. 165

SAIC
An Employee Owned Company

Overview of Advanced Railgun Diagnostics

Diagnostics	Measured or Inferred Parameters	Issues	Selected References
Magnetic B-dots	• Armature current distribution • Armature location	• 3-D structure • Quasi-steady assumptions • Orientation	Cobb, et al. - Ref. 1, p. 189 - Ref. 3, p. 507 Jamison, et al. - Ref. 2, p. 256 Parker - Ref. 3, p. 487 Smith, et al. -Ref. 3, p. 501 Bouvier - Ref. 3, p. 516
On-board diagnostics	• Projectile acceleration and velocity profiles	• Soft-catch • Vibrations • Mass/volume of package	Fernandez, et al -Ref. 1, p. 185 Littrell, et al. - Ref 4 Grzesik, et al. - Ref. 1, p. 147

SAIC
An Employee Owned Company

Overview of Advanced Railgun Diagnostics

Diagnostics	Measured or Inferred Parameters	Issues	Selected References
Visar	• Velocity profiles	• Shock heating of ambient gas • Vaporization of projectile/bore • Blowby • Projectile deflection/ deformation • Mechanical vibrations	Asay, et al. - Ref. 2, p. 46
Calorimetry	• Total thermal energy delivered to surface	• High powers	Derbidge, et al. -Ref. 1, p. 202
Radiometry	• Heat flux	• High powers • Vibration sensitivity	Ibrahim - Ref 5, p. 2045

SAIC.
An Employee Owned Company

Reference List for Diagnostics Table

1. IEEE Trans. on Magnetics *27*, Jan. 1991
2. IEEE Trans. on Magnetics *25*, Jan. 1989
3. IEEE Trans. on Plasma Science, June 1989
4. Third European Symposium on EML Technology
5. J. Phys. D: Appl. Phys. *13*, (1980)

SAIC

An Employee Owned Company

Summary

- Some railgun research is relevant to ETC technology
  - Plasma physics
  - Plasma/solid/liquid interactions
  - Diagnostics
  - Data analysis
- Railgun literature is well-documented and readily available
- Expect surprises

INTENTIONALLY LEFT BLANK.

IN-BORE POSITION AND VELOCITY MEASUREMENT TECHNIQUES

R. Richard Bartsch and Harold A. Davis
Los Alamos National Laboratory
Los Alamos, NM 87544

ABSTRACT

A mode-launcher has been developed which permits in-bore microwave interferometry in the lowest propagating mode (TE_{11}). This technique eliminates multipath and multiple mode problems which can occur with a launcher external to the gun barrel, and may result in position data which is clean enough to look at details of the acceleration of the projectile. Tests with a 20mm steam gun will be discussed.

This work performed under the auspices of the U.S. Department of Energy.

R. Richard Bartsch
and Harold A. Davis
Los Alamos National Laboratory

In-Bore Position and Velocity Measurement Techniques

JANNAF Workshop
9-11 July, 1991
Aberdeen, Md

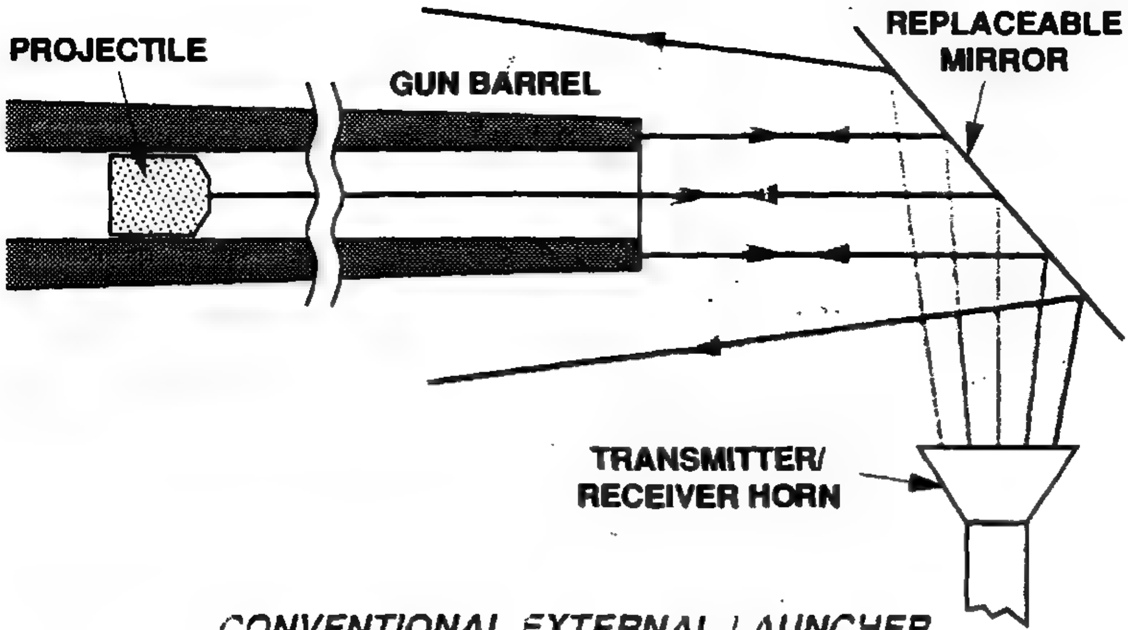
Outline

- Fundamental Mode Microwave Interferometer (20 mm Test Gun)
  ✓ Developed and Demonstrated
  ✓ Position Measurement

- R.F. Modulated Laser Radar
  ✓ Developed and Demonstrated @ 500 MHz
  ✓ Designed 1 GHz System
  ✓ Position Measurement

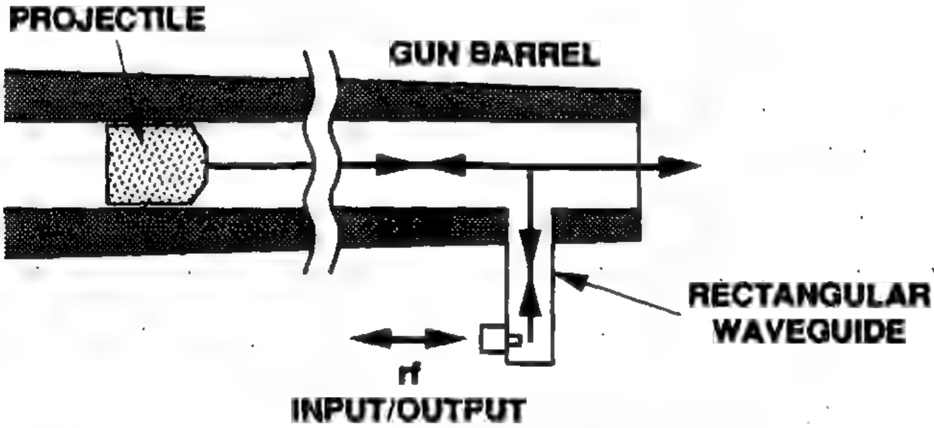
- VISAR (Velocity Interferometer System for Any Reflector)
  ✓ Developed at SNL
  ✓ Refined and Extended at LANL
  ✓ Velocity Measurement

Los Alamos



CONVENTIONAL EXTERNAL LAUNCHER

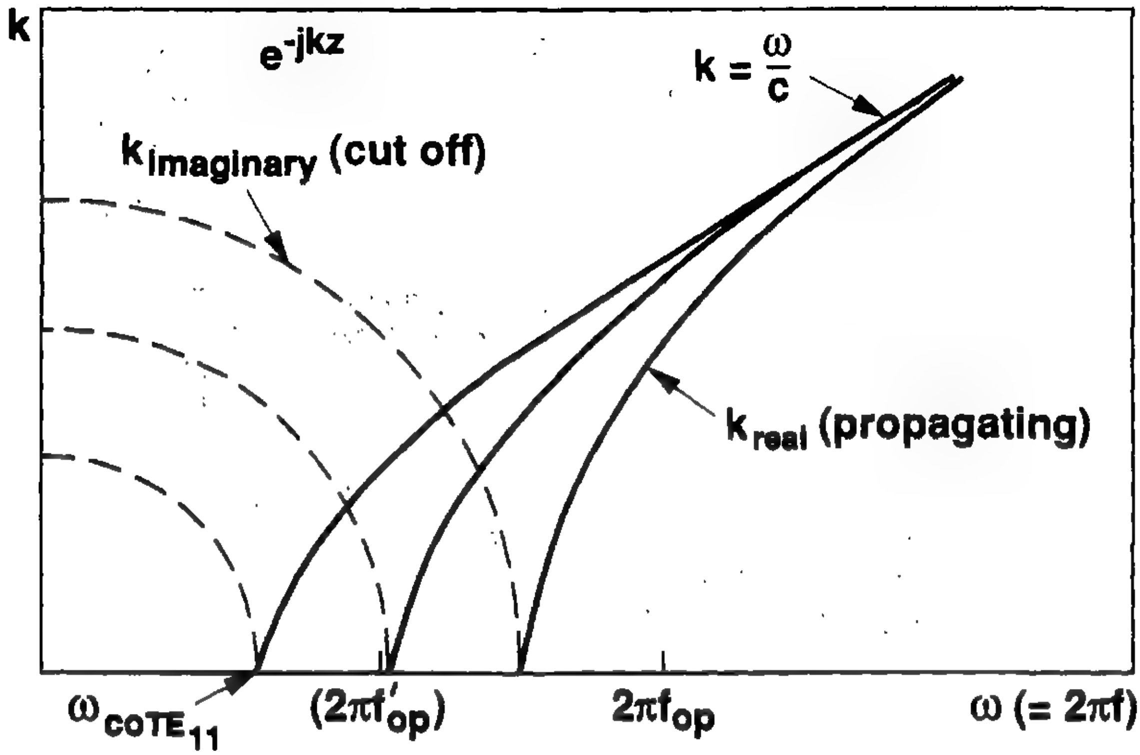
a) INEFFICIENT
b) MULTIPLE PATHS
c) MULTIPLE MODES
d) EASY TO SETUP



FUNDAMENTAL MODE LAUNCHER

a) MECHANICAL DESIGN TO WITHSTAND BLAST
b) SINGLE MODE
c) EFFICIENT

Los Alamos



f = **Frequency**

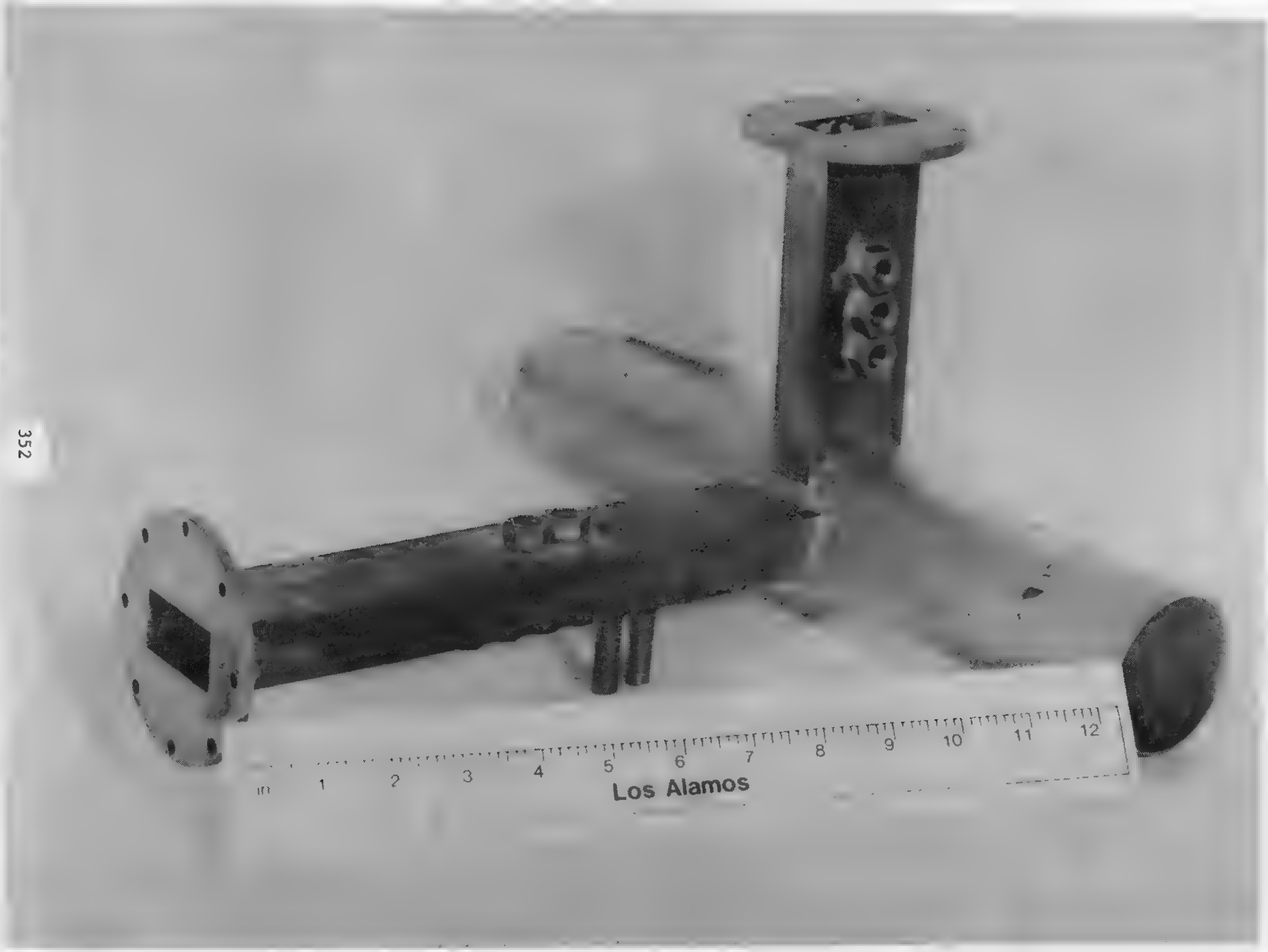
k = **Propagation constant = 2π/guide wavelength**

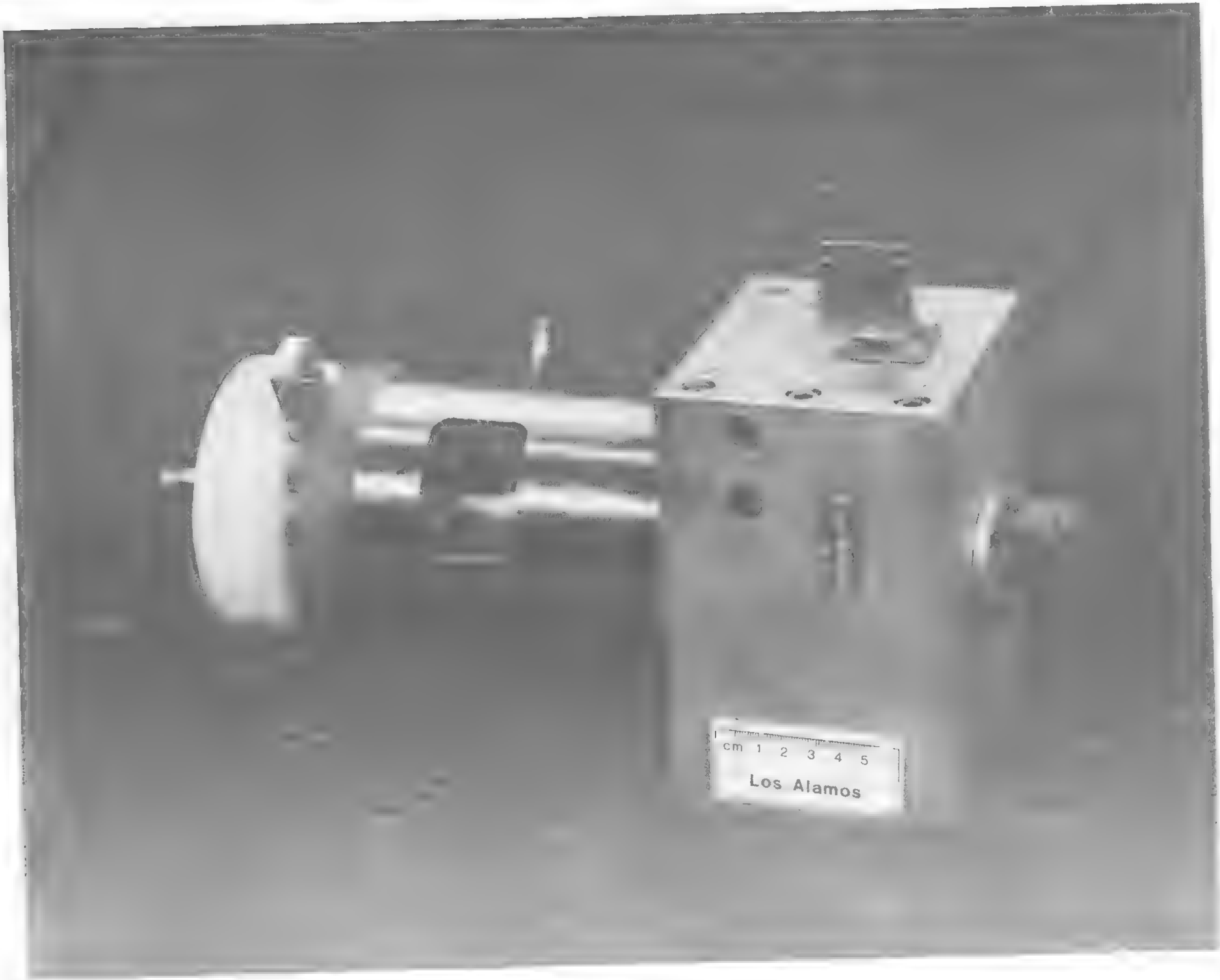
f_{op} = Operating frequency of conventional interferometer

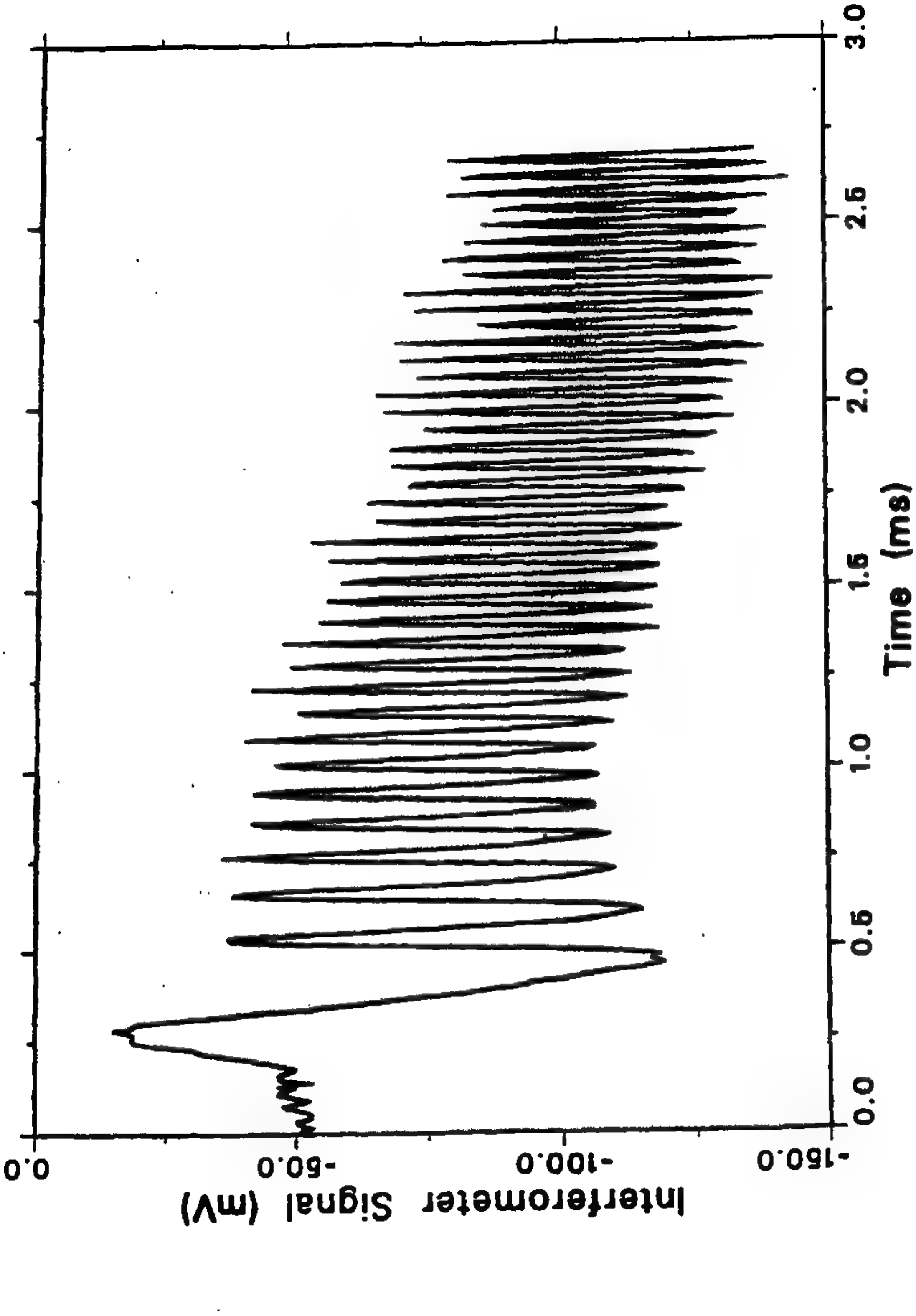
f'_{op} = Operating frequency of fundamental-mode interferometer

PROPAGATION OF WAVEGUIDES MODES

Los Alamos

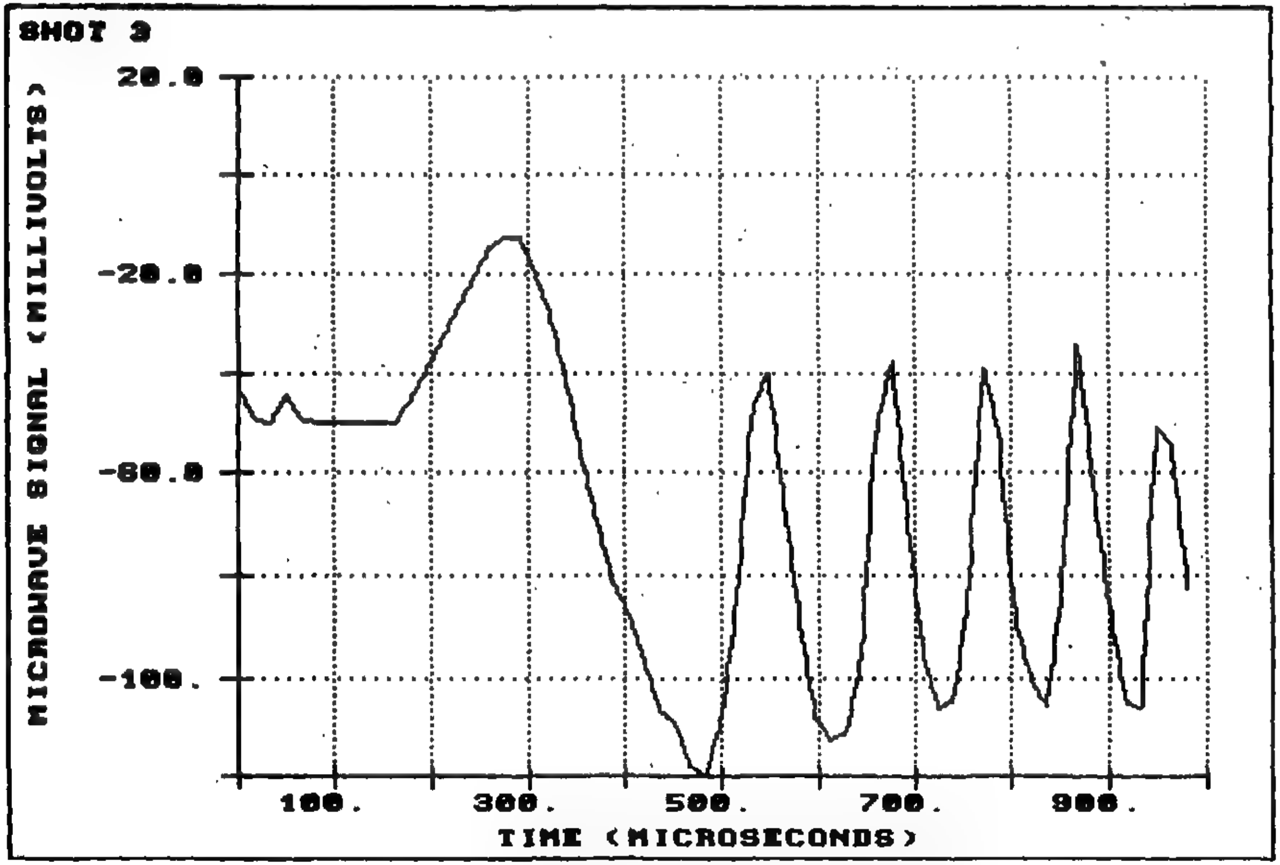

Los Alamos


cm 1 2 3 4 5
Los Alamos

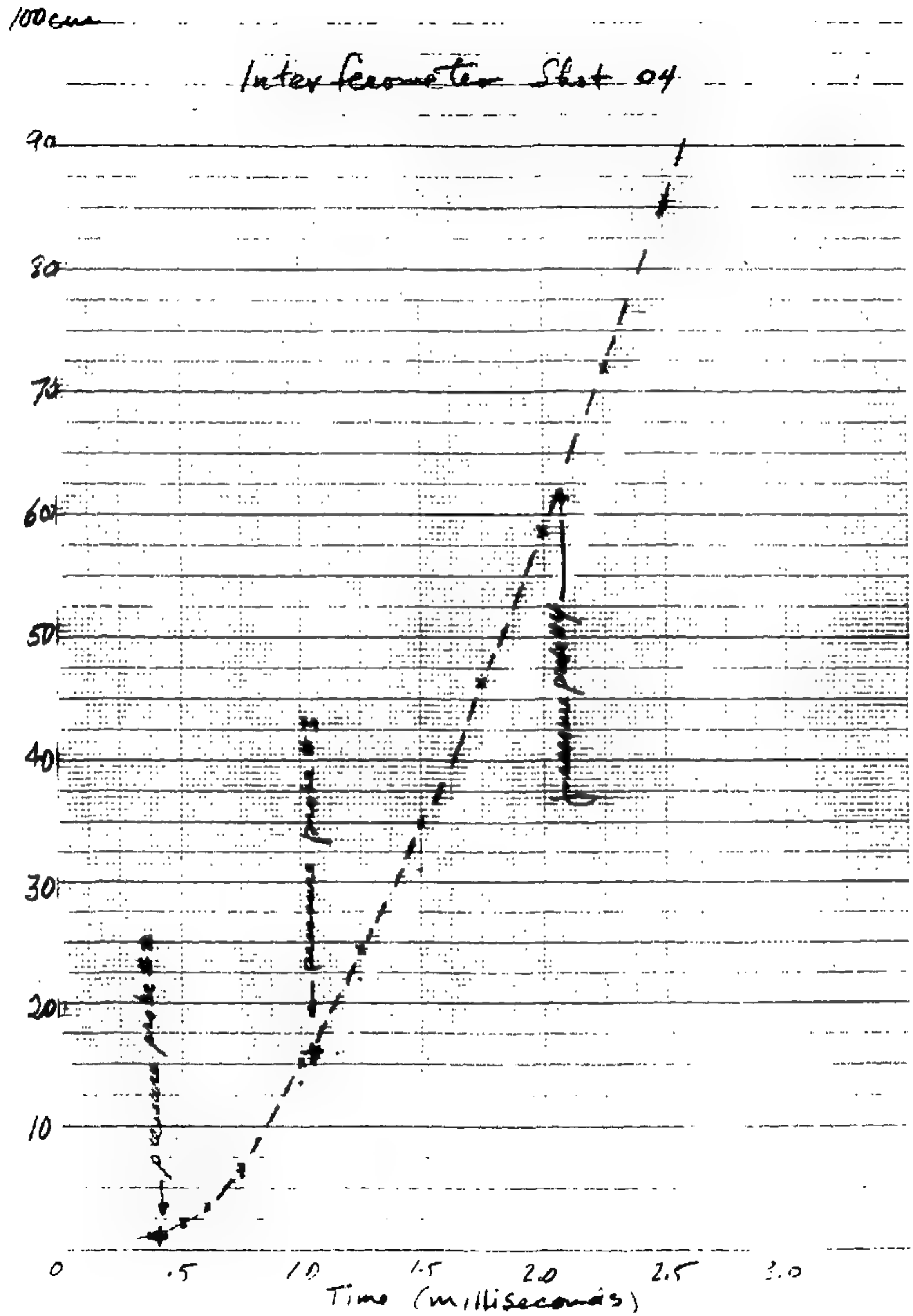


Time (ms)
Interferometer Signal (mV)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.0
-50.0
-100.0
-150.0

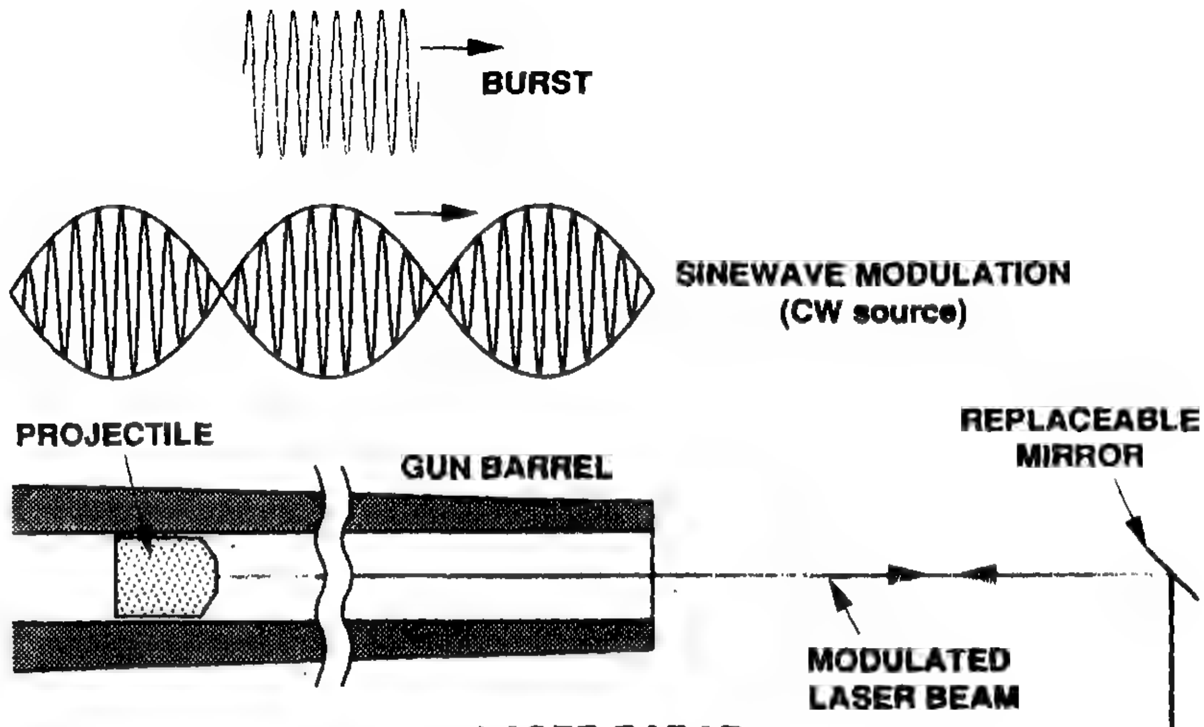
Microwave Interferometer Signal



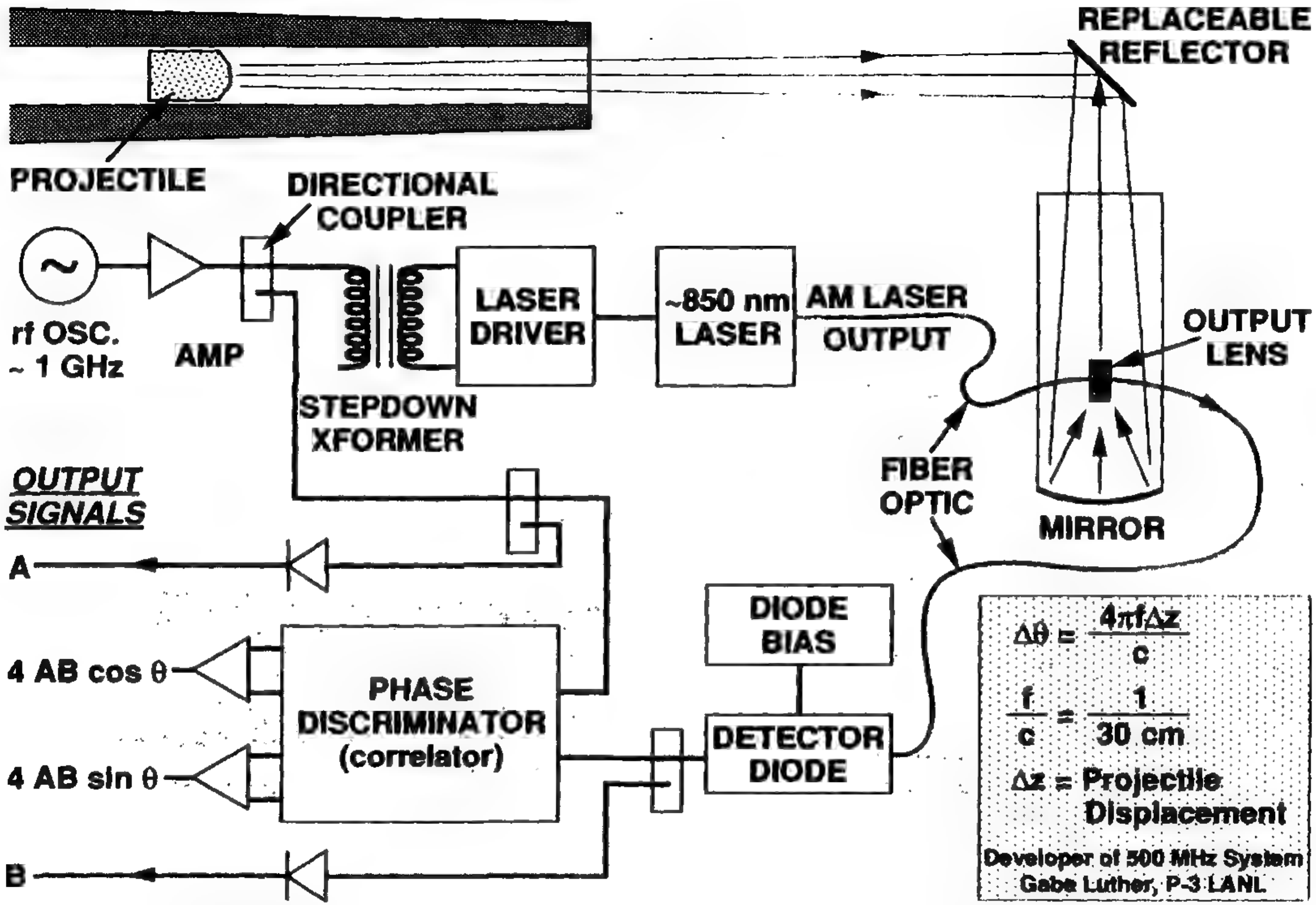
Los Alamos



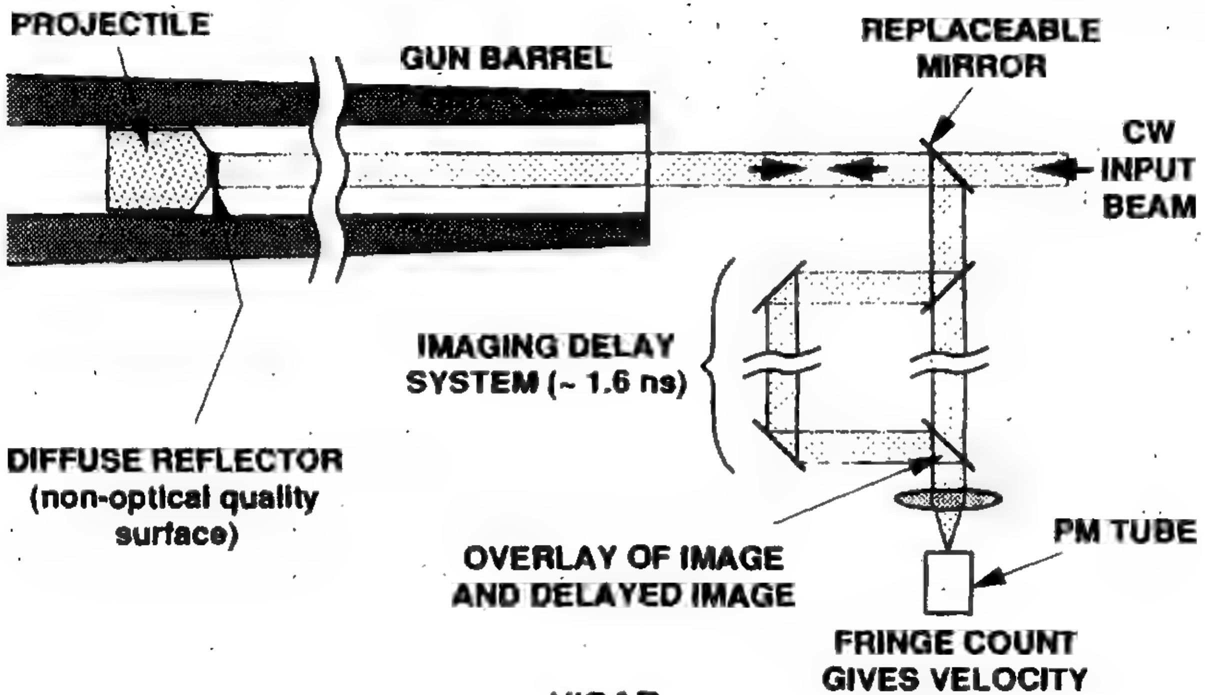
100 cm
Interferometer Shot 04
90
80
70
60
50
40
30
20
10
0
.5
1.0
1.5
2.0
2.5
3.0
Time (milliseconds)


BURST
SINEWAVE MODULATION
(CW source)
PROJECTILE
GUN BARREL
REPLACEABLE
MIRROR
MODULATED
LASER BEAM

LASER RADAR

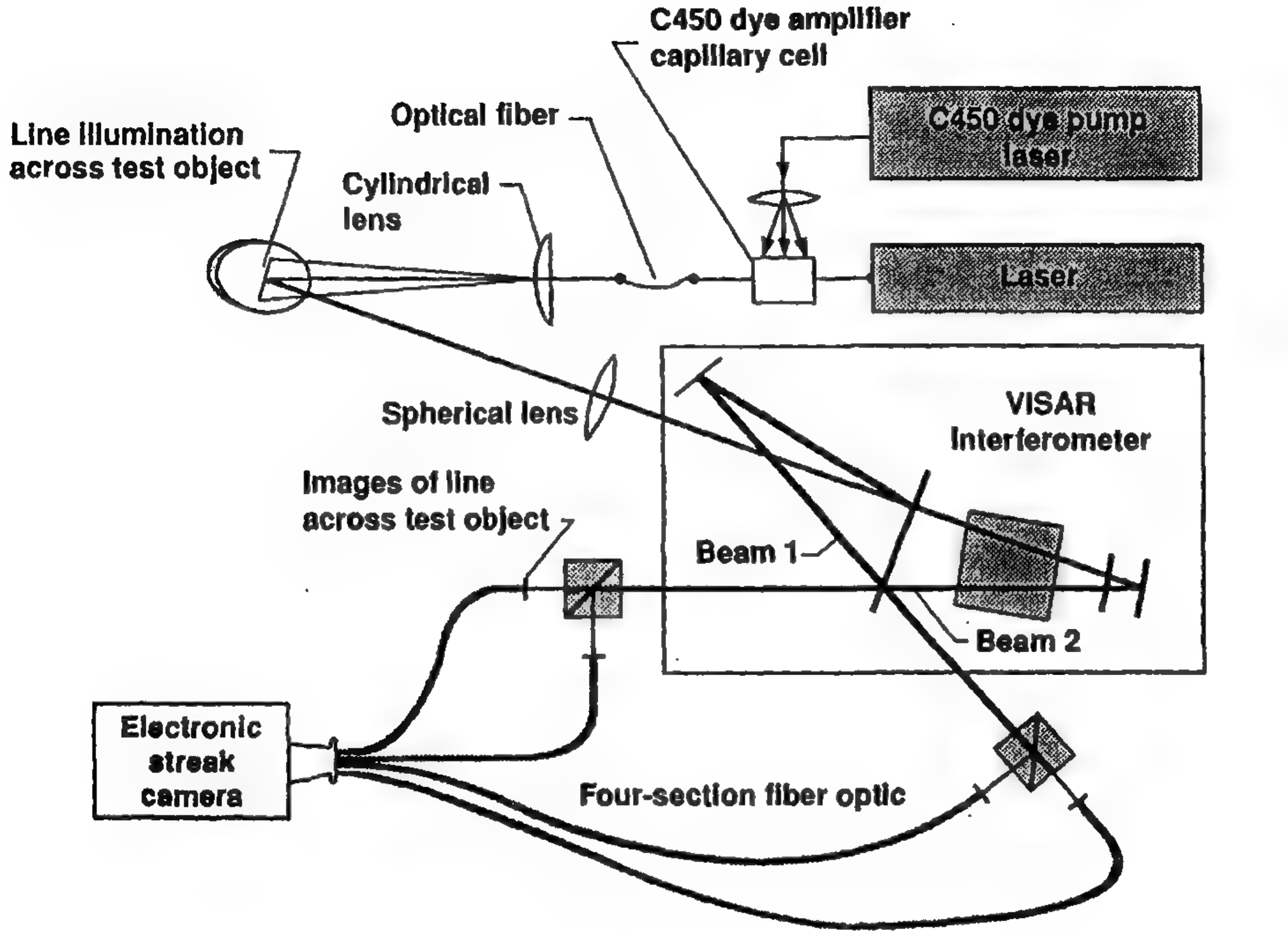


rf MODULATED-LASER-BEAM POSITION SENSOR

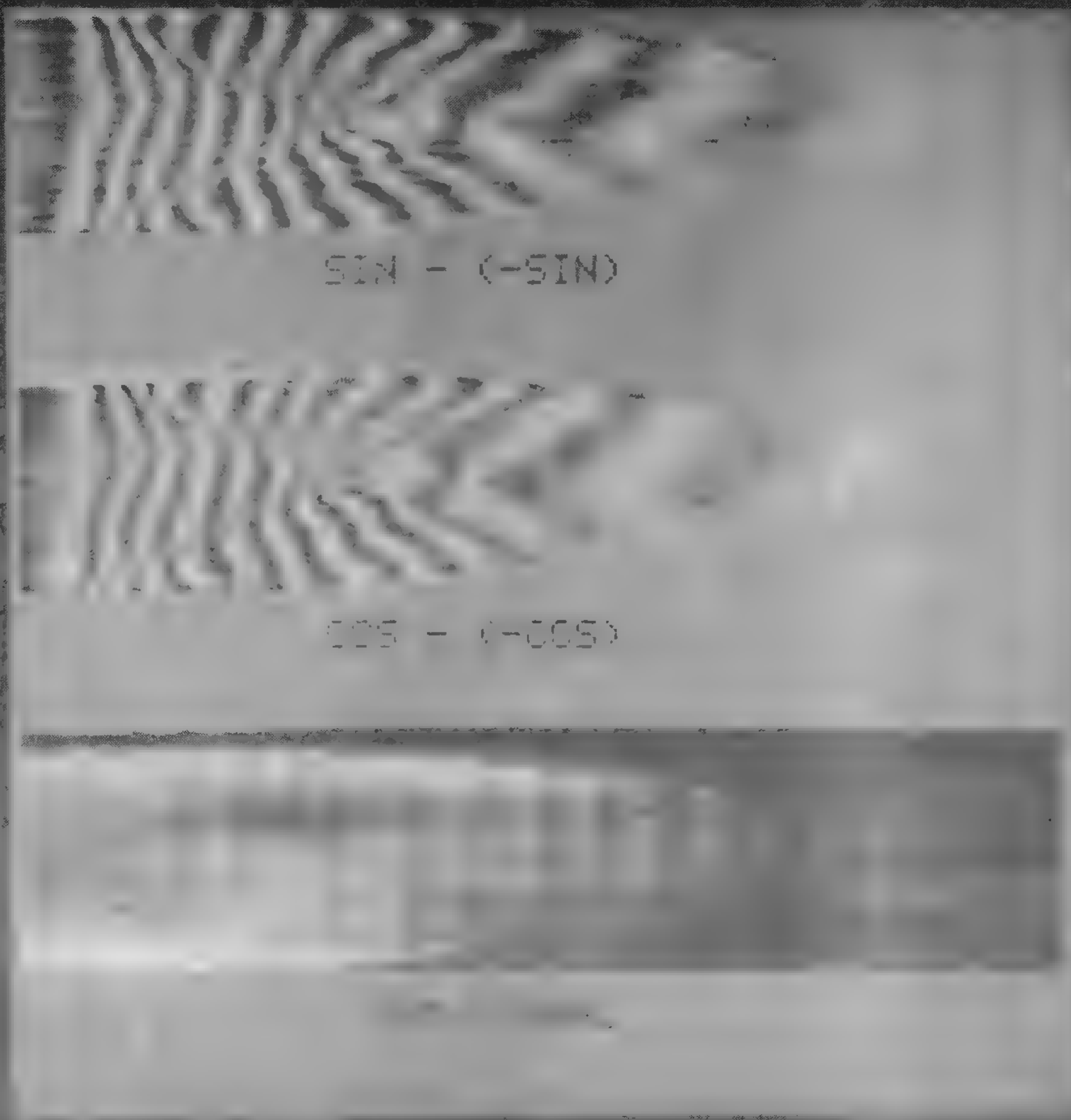


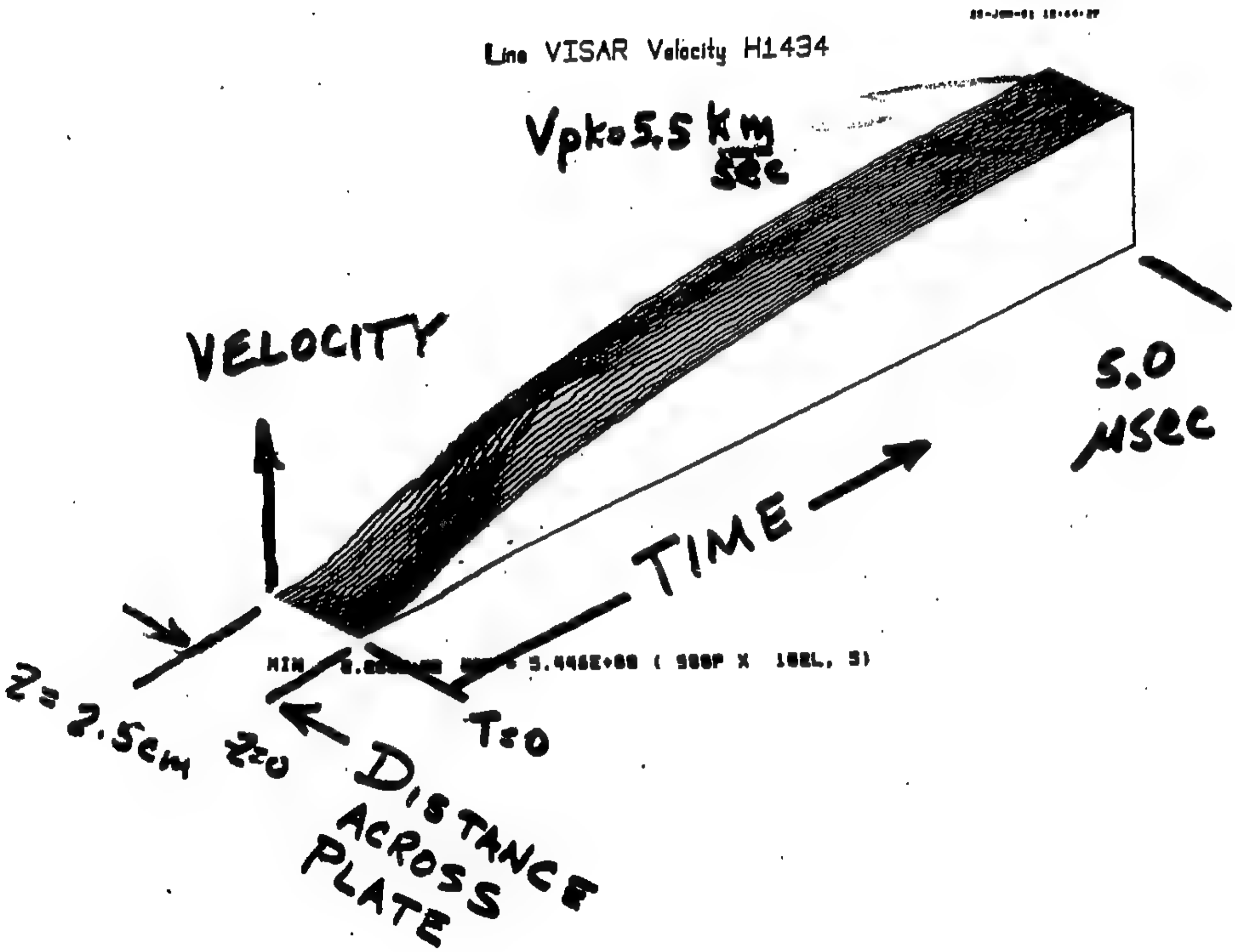
VISAR

Los Alamos



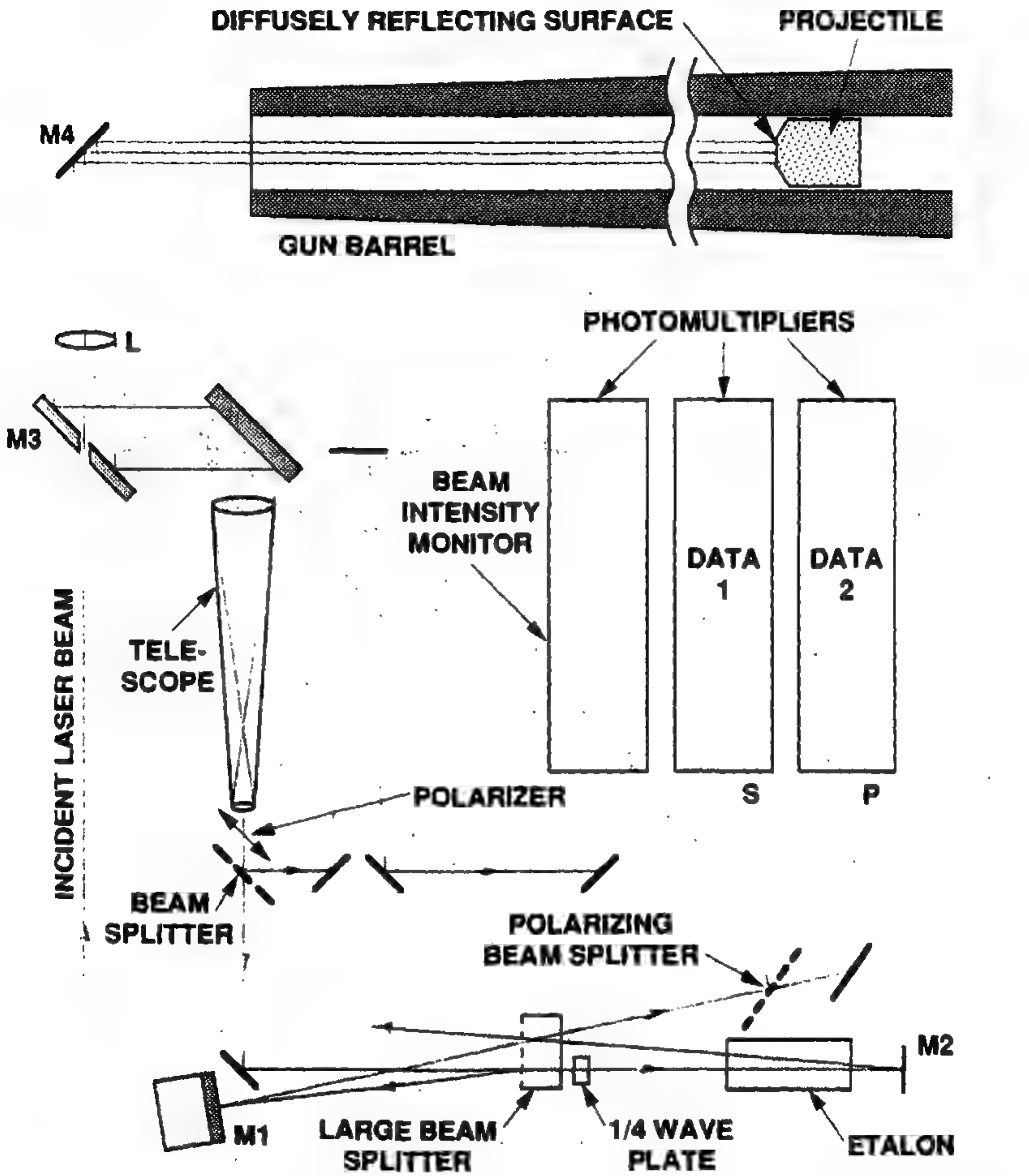
c/o Will Hemsing
M-4
LANL


SIN - (-SIN)
COS - (-COS)



Line VISAR Velocity H1434
Vpk=5.5 km/sec
VELOCITY
5.0
μsec
TIME
T=0
Z=2.5cm
Z=0
DISTANCE
ACROSS
PLATE

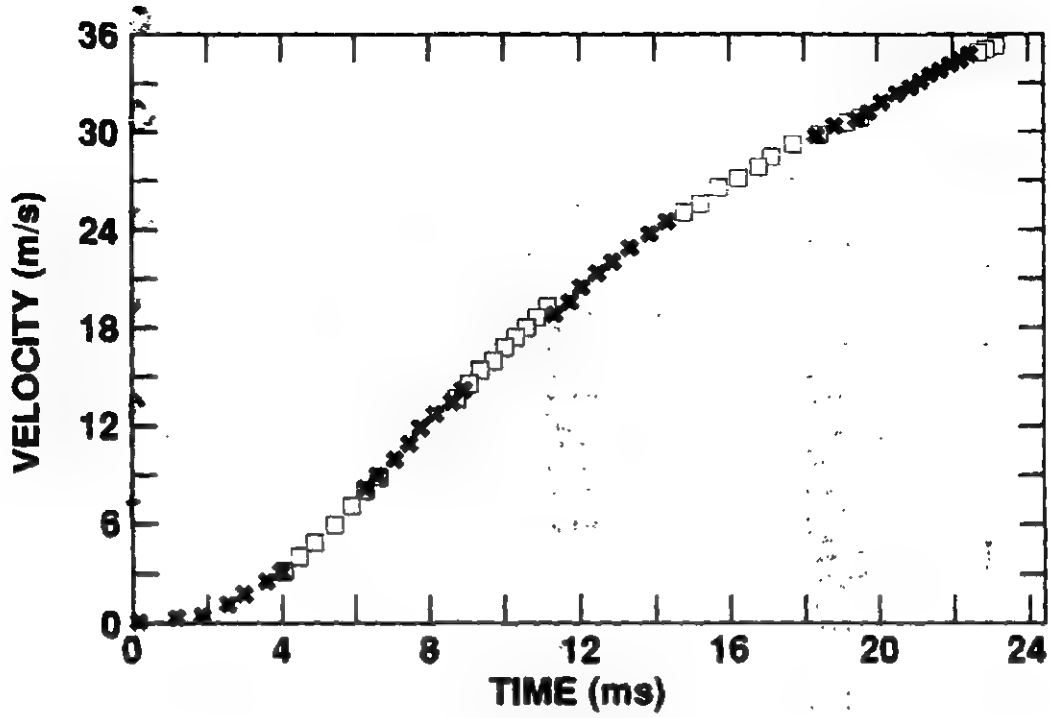
P-1/Db-c22



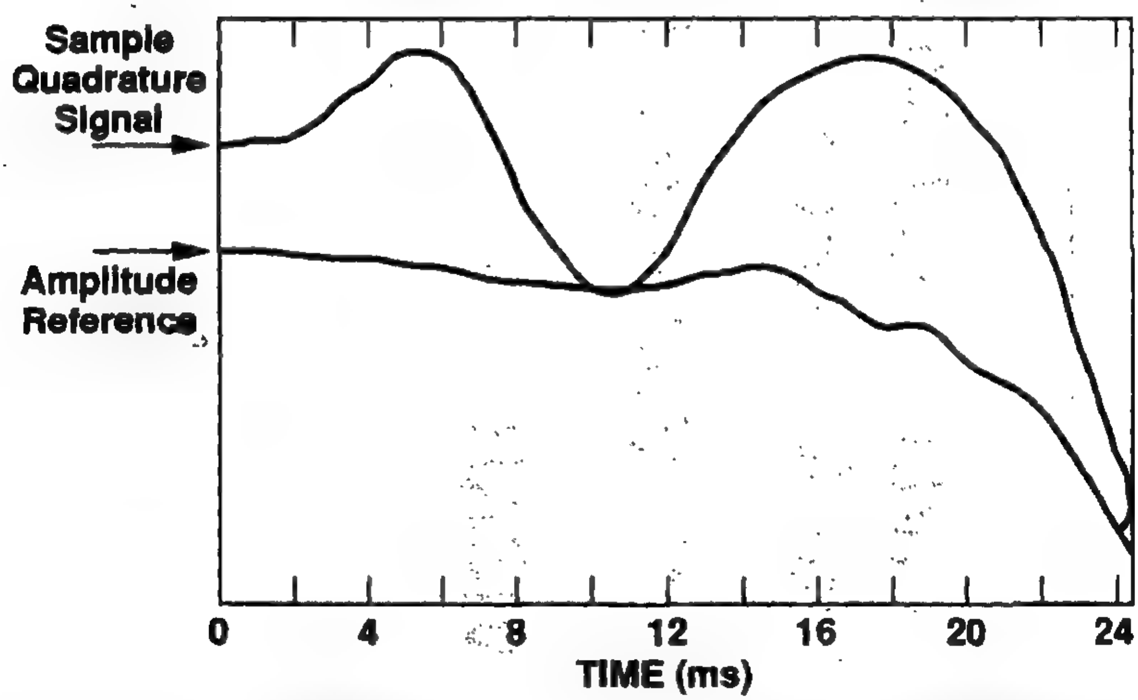
SCHEMATIC OF A VISAR SYSTEM

ref. Barker and Hollenbach,
J. Appl. Phys. Vol. 43, No.11, 4669

Los Alamos



PROJECTILE VELOCITY vs TIME



FRINGE DATA FOR PROJECTILE MOTION

ref. Barker and Hollenbach,
J. Appl. Phys. Vol. 43, No.11, 4669

Los Alamos

Summary

- Fundamental-Mode Microwave Interferometer
- R.F. Modulated Laser Radar
- VISAR

Los Alamos

INTENTIONALLY LEFT BLANK.

IN-BORE ACCELERATION MEASUREMENTS WITH AN INSTRUMENTED RAILGUN PROJECTILE

Donald M. Littrell, Keith A. Jamison and Glenn E. Rolader
U.S. Air Force Armament Directorate
Eglin AFB, FL 32542-5434

ABSTRACT

An instrumented package has been accelerated in an electromagnetic launcher to measure the in-bore acceleration as a function of time. Direct, continuous acceleration profiles of the launch show the gas injection phase, electromagnetic propulsion, and downrange deceleration in a softcatch recovery system. These proof-of-principle experiments were conducted in a 50 mm square bore railgun and utilized off-the-shelf components for the in situ measurement, digitization, and storage of acceleration data. The 1.2 kg launch package was subject to peak accelerations of nearly 30 kilogees (2.8 X 10^5 m/s^2) in the electromagnetic propulsion phase of the launch. Velocity and position data obtained through integration of this data are correlated with velocity data derived from conventional static diagnostics (e.g., magnetic flux loops) to validate the technique. The peak acceleration was slightly more than anticipated from the electrical current delivered to the railgun, and this deviation is examined. The presentation includes a description of the experimental apparatus, acquired data, a comparison of the data with code simulations, and suggestions for further application of this diagnostic for in-bore ballistic measurements.

IN-BORE ACCELERATION MEASUREMENTS WITH AN INSTRUMENTED RAILGUN PROJECTILE

PRESENTED AT

JANNAF Workshop on Electrothermal-Chemical Modeling and Diagnostics

Aberdeen Proving Ground, MD

July 9-11, 1991

PRESENTER

Donald M. Littrell, USAF, WL/MNSH

CONTRIBUTORS

Keith A. Jamison, SAIC
Glenn E. Rolader, SAIC

PRESENTATION OUTLINE

- PROGRAM OVERVIEW
- EQUIPMENT
- PRELIMINARY TESTS
- EML TESTS
- DATA ANALYSIS
- SUMMARY

PROGRAM DEFINITION

In-Bore Instrumentation/Diagnostics (IBID)

The use of self-contained, on-board instrumentation to measure and explore the projectile environment within an electromagnetic gun during launch.

PROGRAM GOALS

- CONSTRUCT A PROJECTILE TO ACQUIRE AND STORE DATA DURING ACCELERATION BY AN ELECTROMAGNETIC LAUNCHER

- EXPAND THE KNOWLEDGE BASE ON PROJECTILE ACCELERATION VIA THE APPLICATION OF MAGNETIC FORCES

- FURTHER THE DEVELOPMENT OF GUN-LAUNCHED, SMART PROJECTILES TO VERY HIGH VELOCITIES

IBID CRITICAL ISSUES

- SURVIVABILITY OF ELECTRICAL COMPONENTS AND SENSORS IN THE EML'S TRANSIENT ELECTROMAGNETIC FIELDS

- ELECTRONIC HARDENING AGAINST THE EML'S HIGH ACCELERATION (G) AND TIME RATE OF CHANGE OF ACCELERATION (G-DOT)

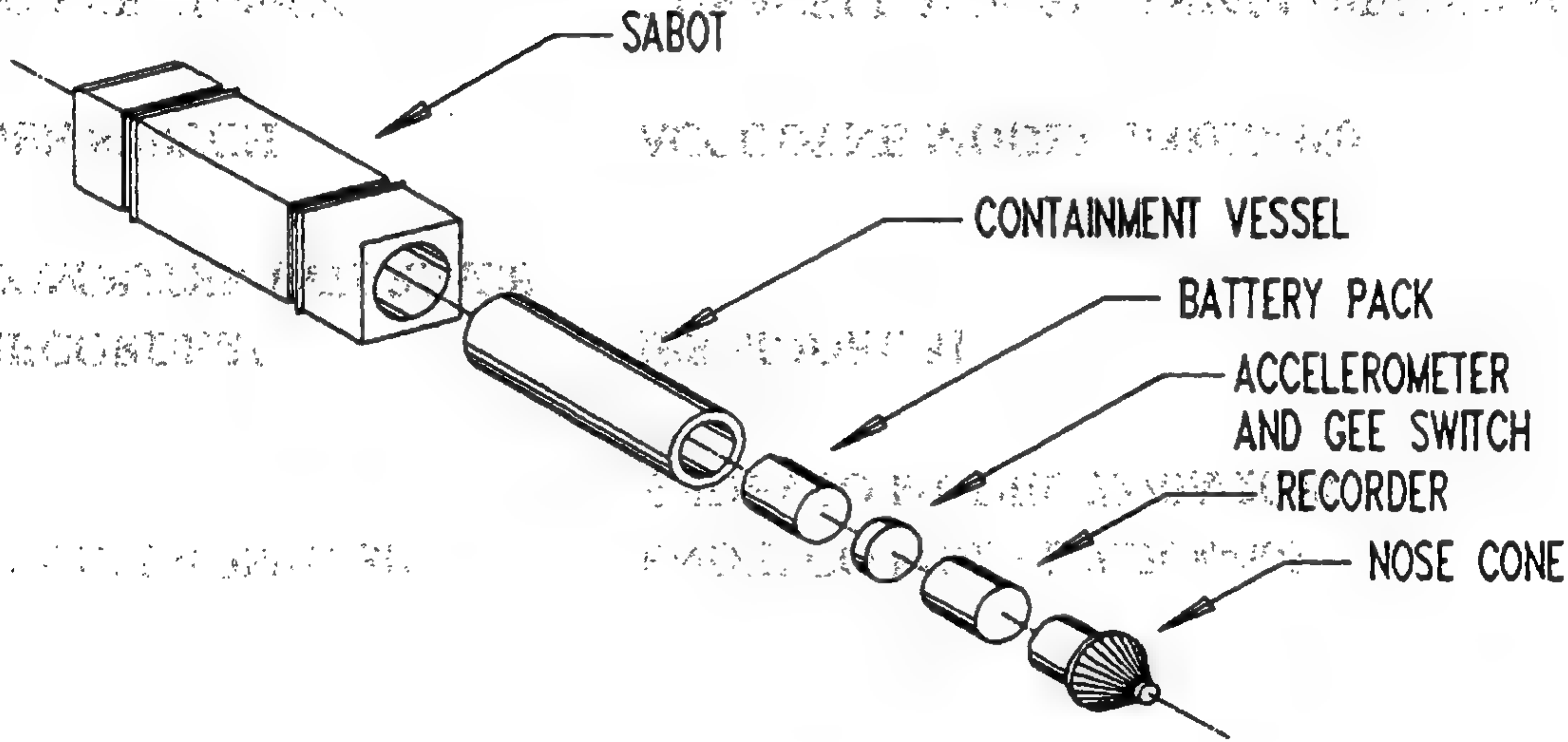
- DEVELOPMENT OF A SOFT CATCH SYSTEM TO STOP A HIGH VELOCITY PROJECTILE WITHOUT DAMAGE

PROJECTILE/EML INTERFACE ISSUES

CHARACTERIZATION OF IN-BORE GUN ENVIRONMENT

- JERK (G-DOT) DURING CURRENT RISE
- MAGNETIC FIELDS
- BALLOTING, EXCESSIVE LATERAL GEES
- NEGATIVE G-DOT IN FORCING CONE
- NEGATIVE G-DOT AT CROWBAR AND EXIT
- MUZZLE WHIP

LAUNCH PACKAGE SCHEMATIC



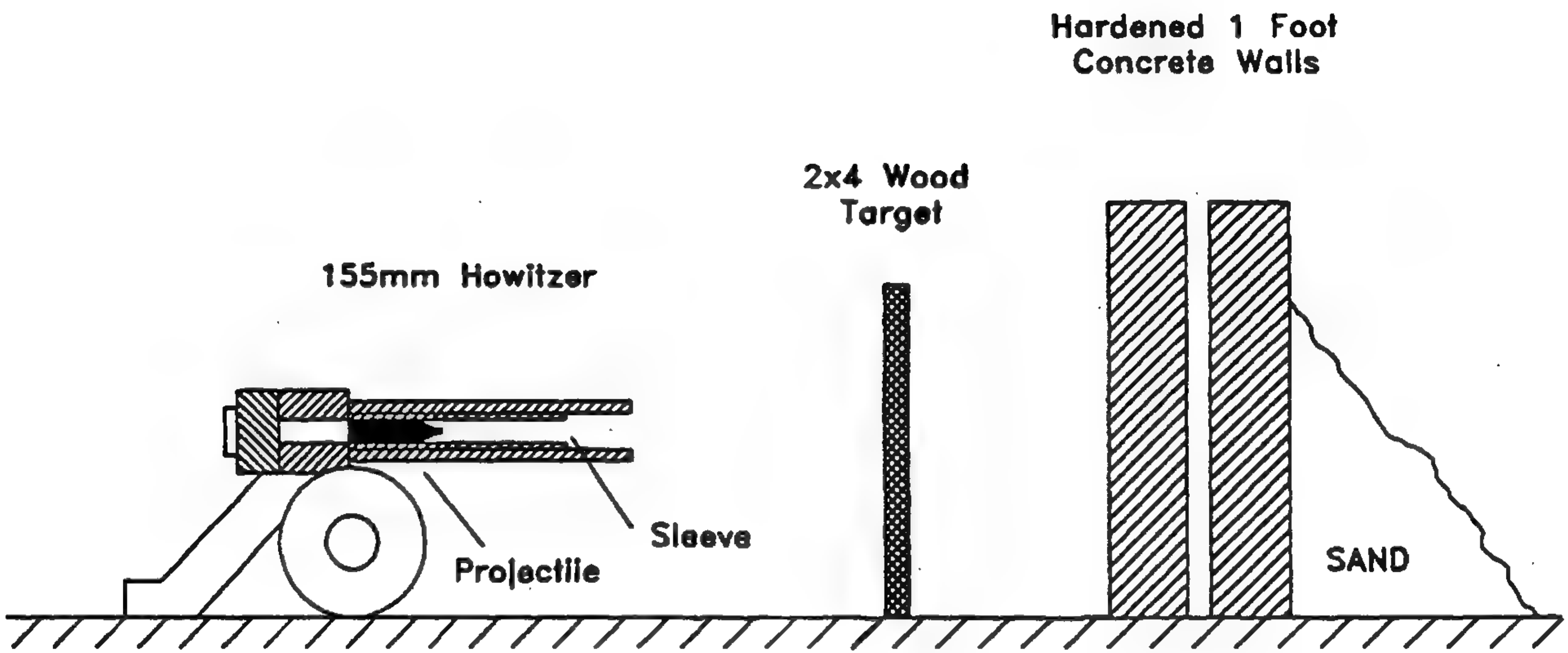
INSTRUMENTATION

ACCELEROMETER	ENDEVCO MODEL 7270A-60K ENDEVCO MODEL 7270A-200K
RECORDER/ COMPUTER INTERFACE	IES MODEL 31
GEE SWITCH	ACCUDYNE MODEL 100050-350
POWER SUPPLY	DURACELL MODEL MN1604 (REPACKAGED)

ACCELEROMETER SPECIFICATIONS

Model #	7270A-60K	7270A-200K
Range (kgees)	60	200
Overrange Limits (kgees)	180	200
Non-Linearity & Hysteresis (%)	± 2	± 2
Transverse Sensitivity (%)	5	5
Frequency Response (kHz)	DC to 100	DC to 150
Mounted Resonant Frequency (kHz)	700	1200
Mass (grams)	1.5	1.5

HOWITZER TEST SETUP



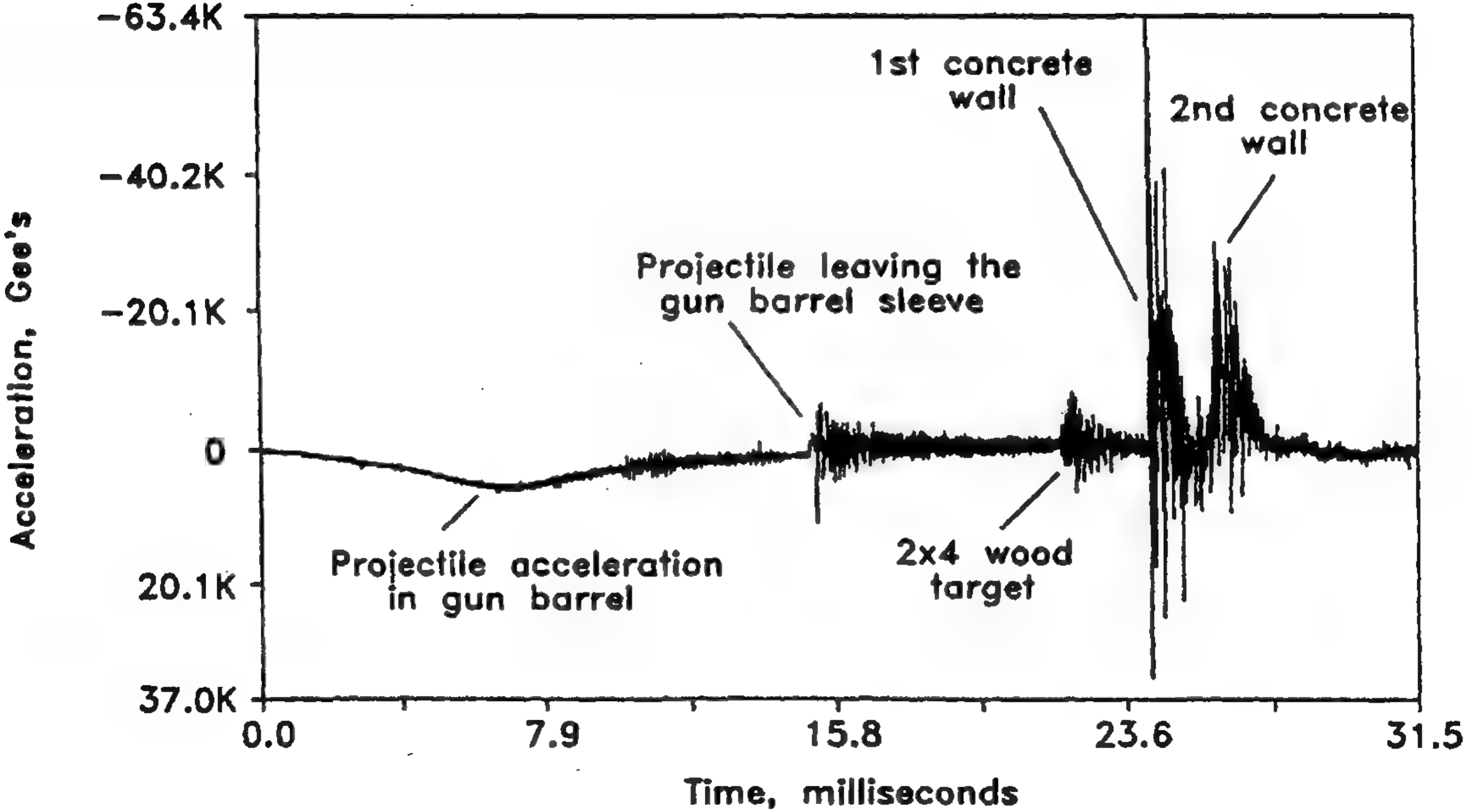
378

RECORDER SPECIFICATIONS

Number of Channels	1
Bandwidth	DC to 300 KHz*
Input	Instrumentation Amplifier
Filter	4 Pole Butterworth*
Amplitude Resolution	8 Bits (256 digital steps)
Storage Capacity	32K Bytes (32K x 8)*
Sample Rate	Up to 2.5 MHz*
Pre-trigger Storage	1762 Bytes
Triggers	Switch Closure or 5 Volt Pulse
Supply Voltage	8 to 15 Volts
Supply Current	
Standby	40 microamps (typical)
Data Acquisition	60 milliamps (typical)
Data Retention	40 microamps (typical)

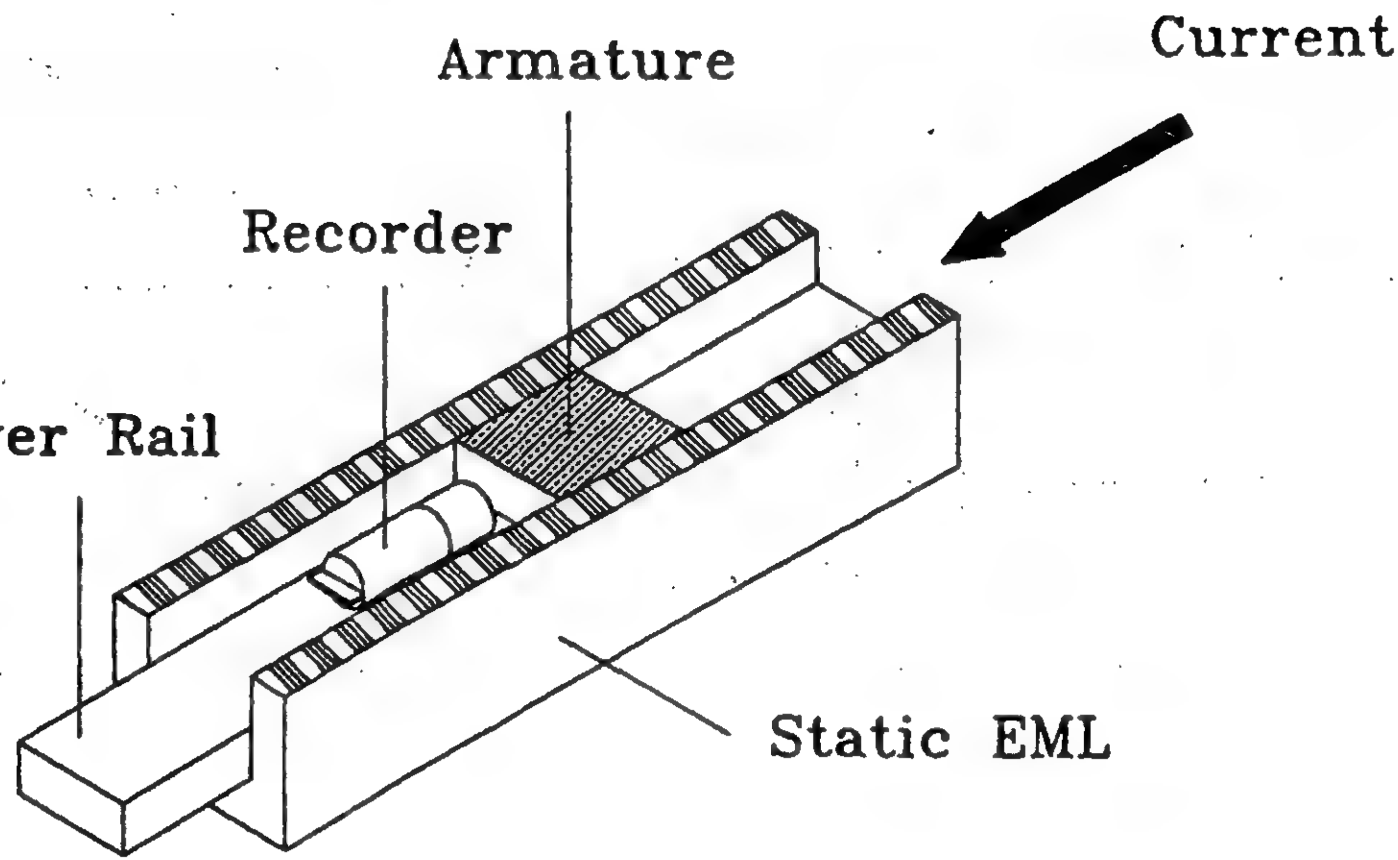
*Selectable at Factory

HOWITZER ACCELERATION DATA



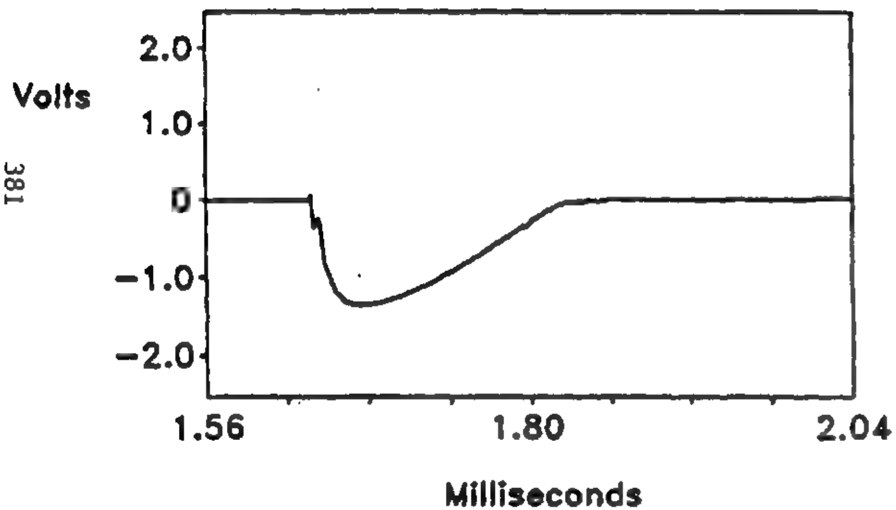
STATIC EML SETUP

Transient Field Effects Analysis

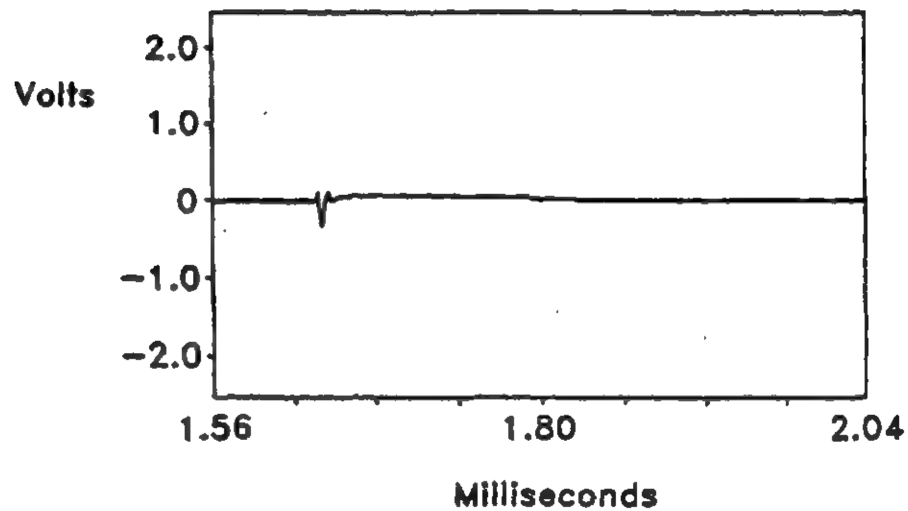


EM INDUCED NOISE

With Respect to Circuit Board Orientation



"Perpendicular"

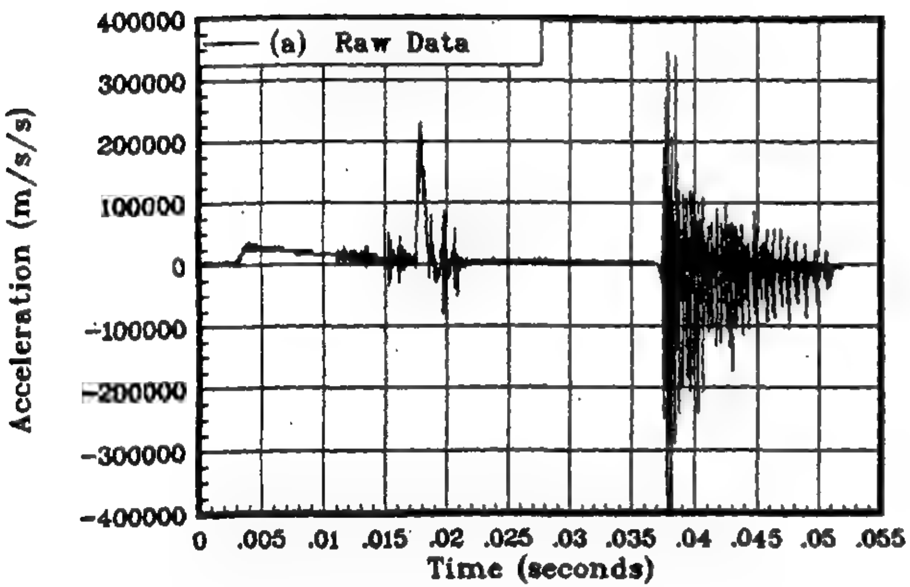


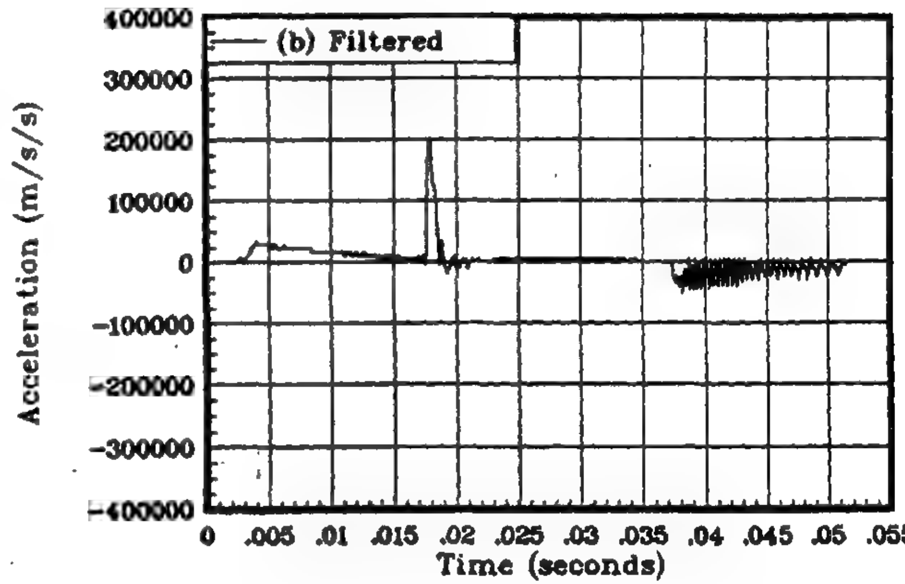
"Parallel"

SUMMARY OF EML ACCELEROMETER TESTS

Test Conditions	PKD	Boeing	IBID197	IBID235
Maximum current (kA)	550	150	821	941
Distance traveled (m)	<1.3	<0.18	>7	>7
Injection velocity (m/s)	—	0	149	162
EML velocity (m/s)	<300	—	264	360
Injector acceleration (kgee)	18	N/A	3.5	3.5
EML peak acceleration (kgee)	12	15	20	28
Projectile mass (kg)	—	—	1.17	1.15
Kinetic energy (kJ)	—	—	48	74
Bore size (mm)	50	25	51	51
Armature type	—	—	plasma	plasma

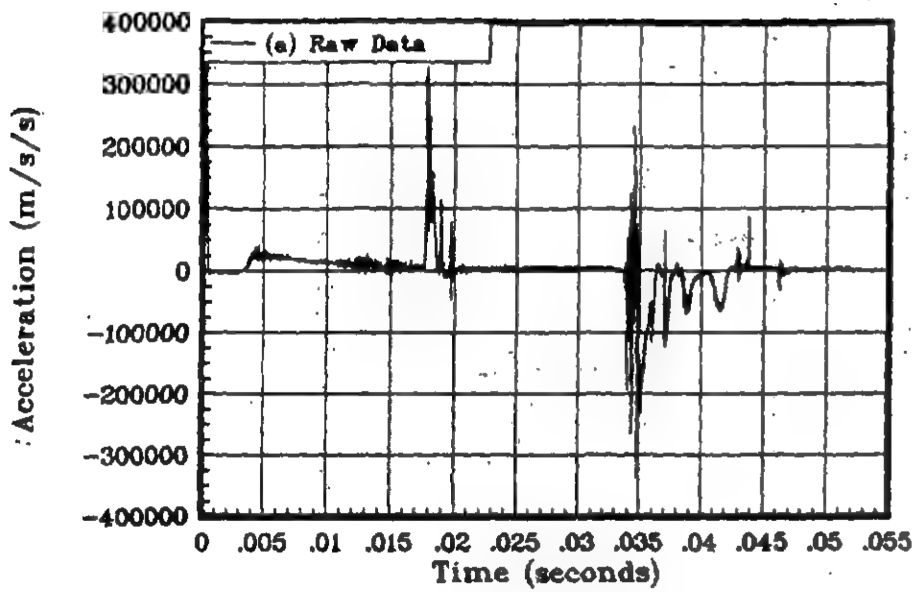
IBID197 ACCELERATION RECORD
(a) Raw Data and (b) Filtered Data (12 kHz)

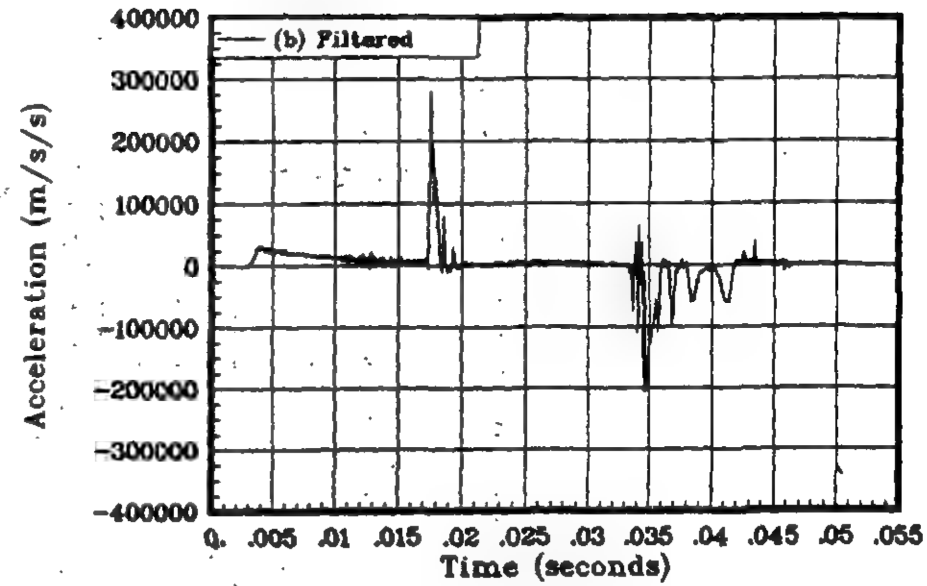




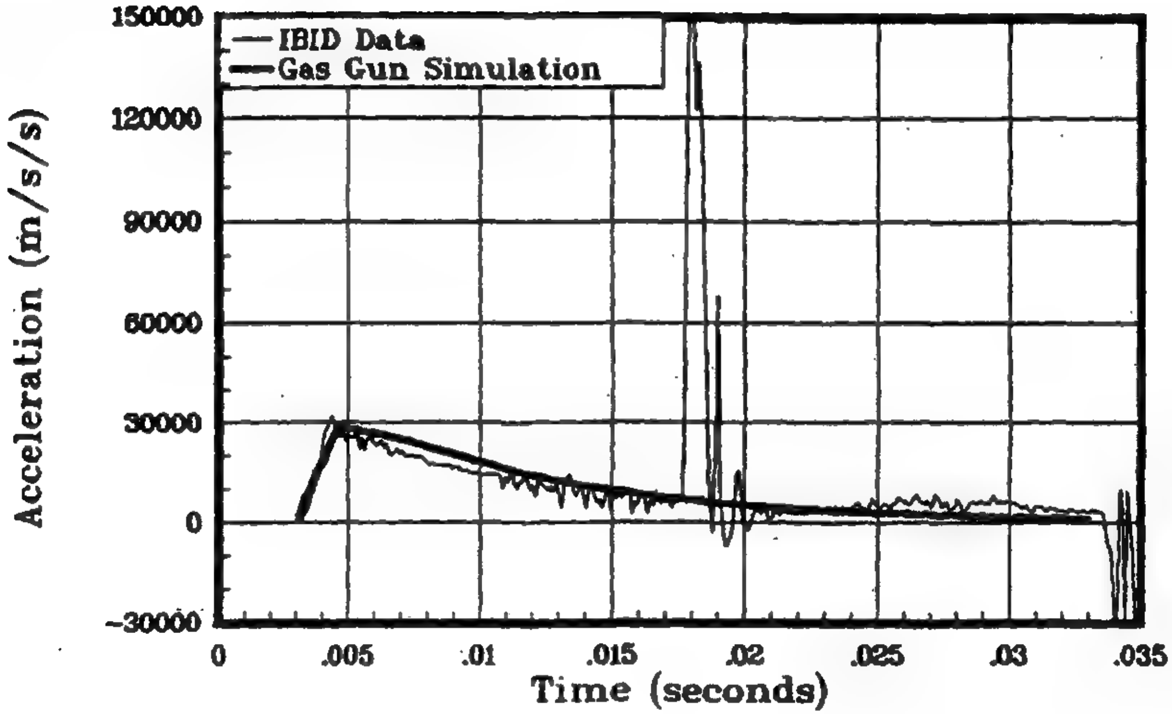
IBID235 ACCELERATION RECORD

(a) Raw Data and (b) Filtered Data (12 kHz)

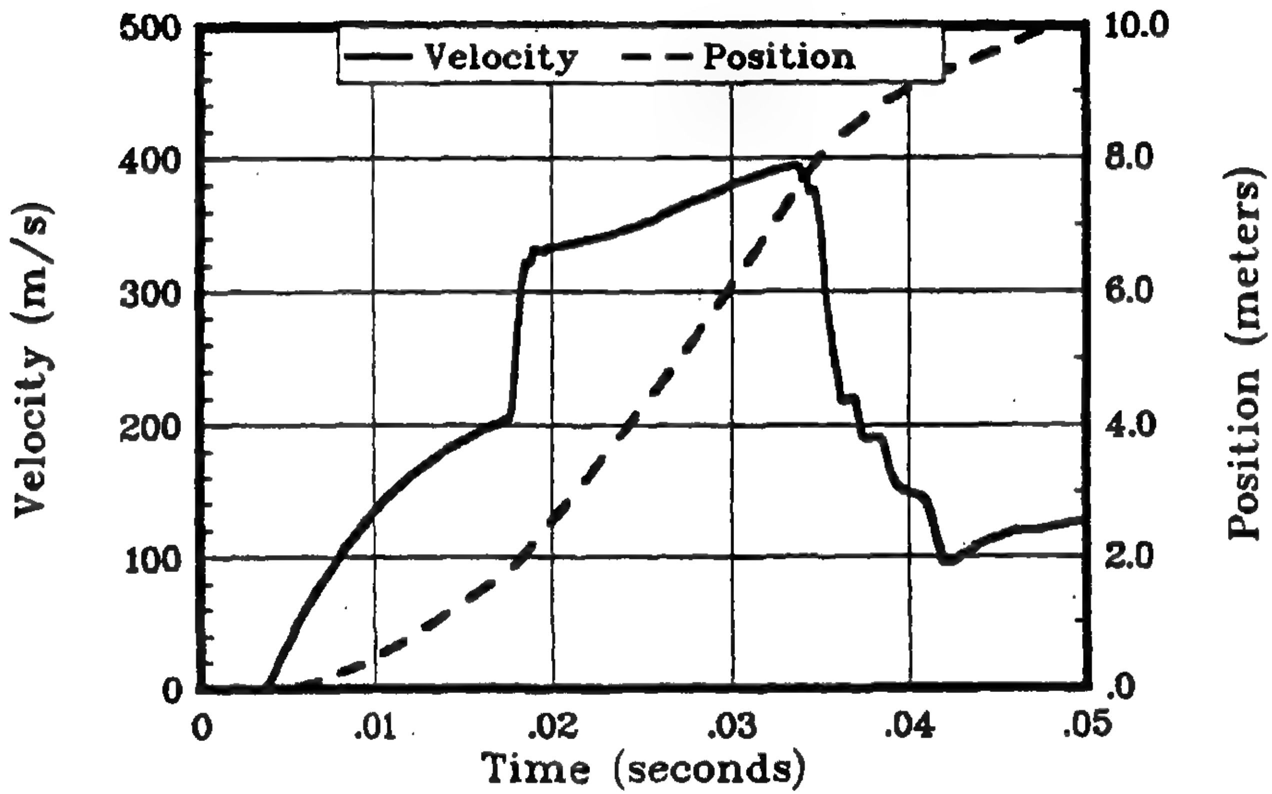




COMPARISON OF IBID235 ACCELERATION WITH GAS GUN SIMULATION

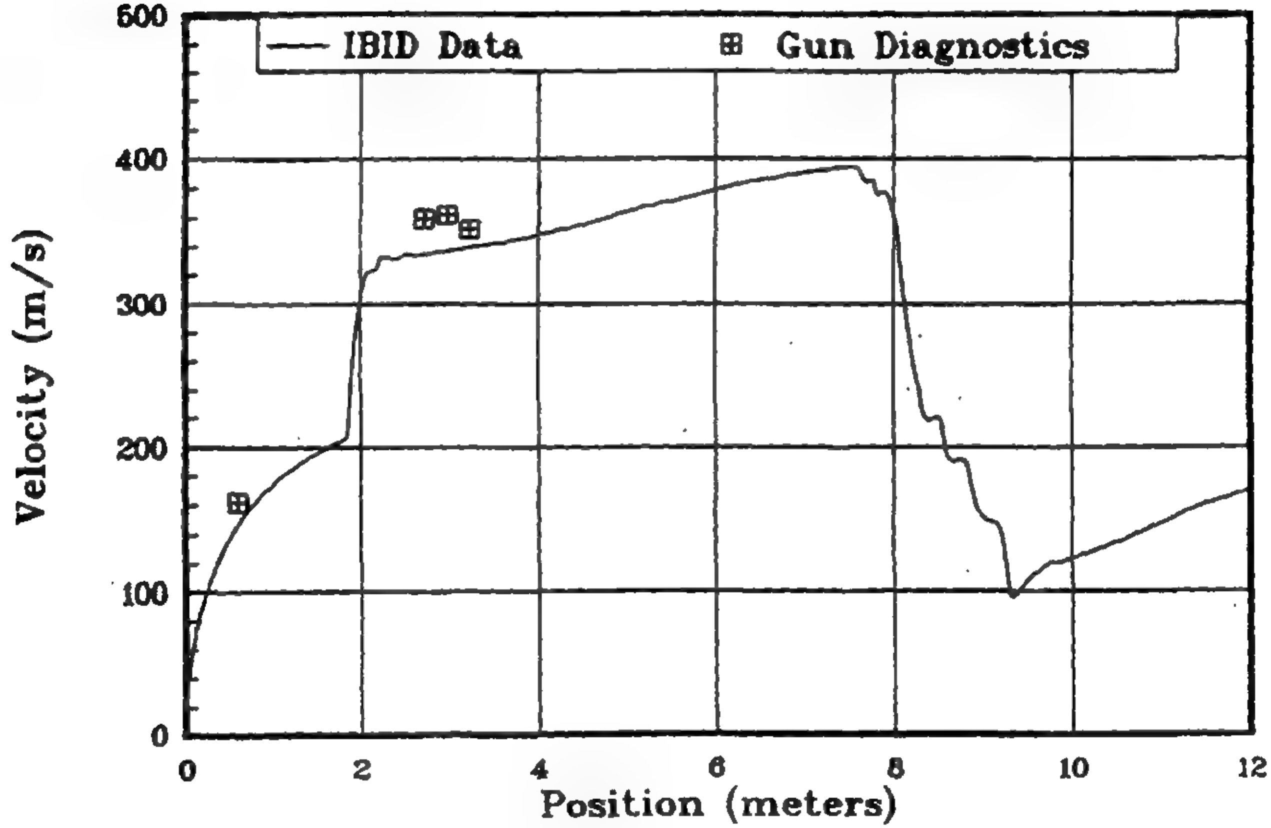


VELOCITY AND POSITION VERSUS TIME
OBTAINED VIA INTEGRATION OF IBID235 DATA



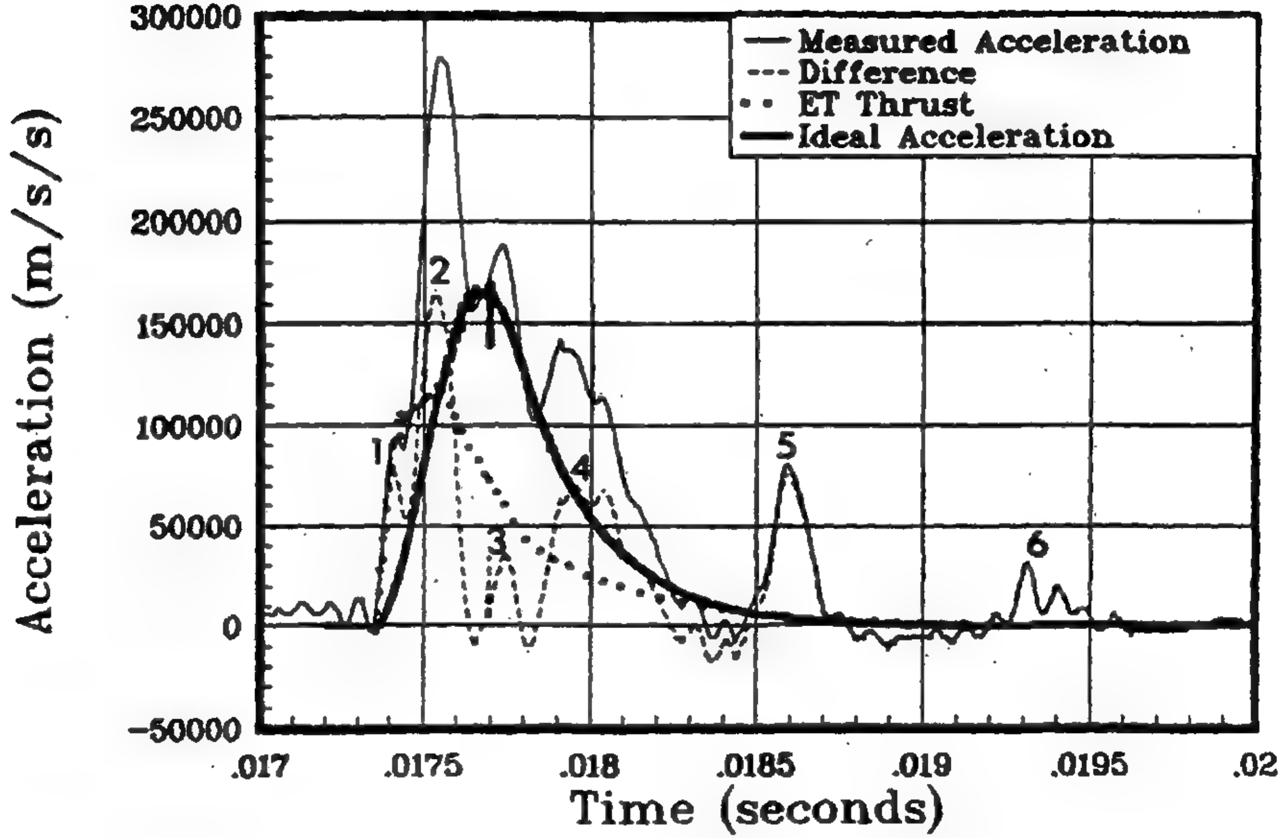
COMPARISON OF VELOCITY MEASUREMENT TECHNIQUES

IBID235



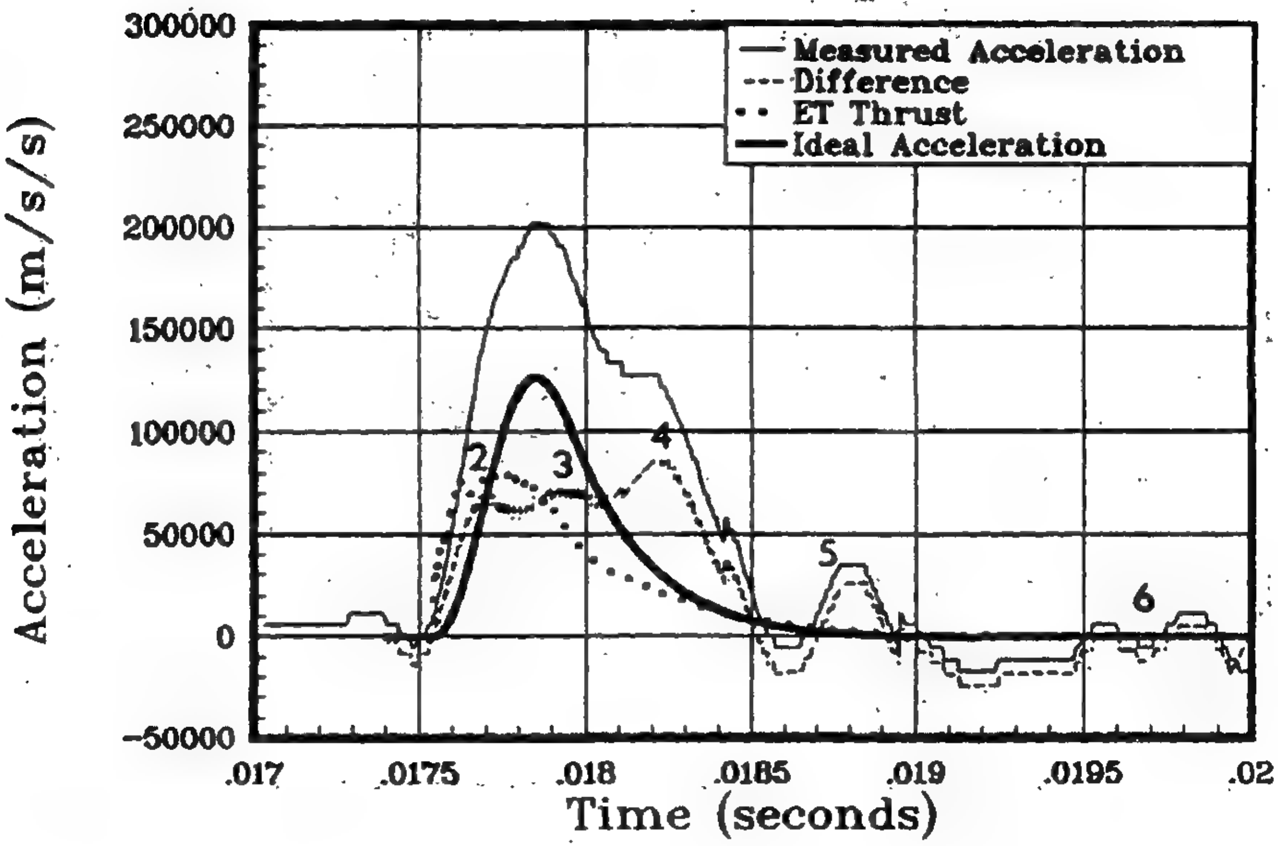
COMPARISON OF MEASURED AND IDEAL ACCELERATION

IBID235



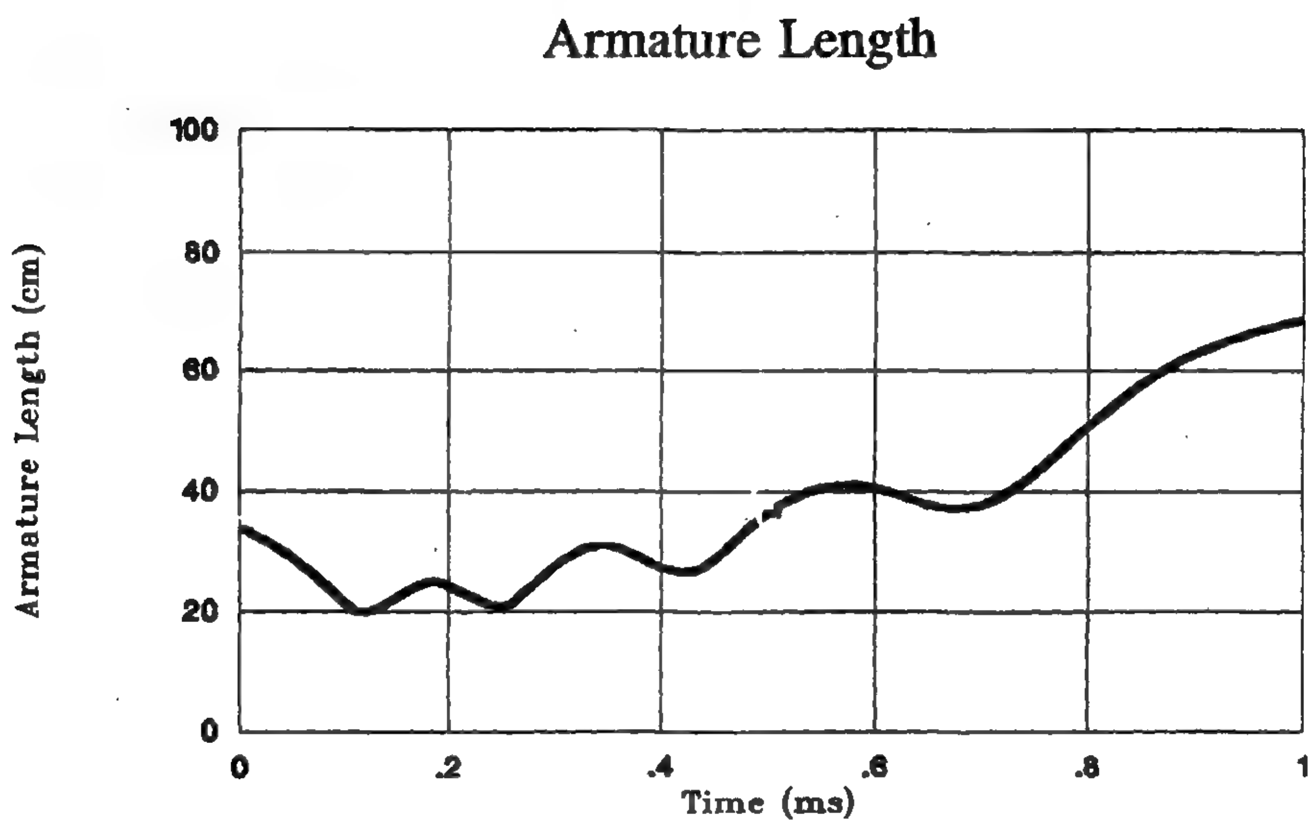
COMPARISON OF MEASURED AND IDEAL ACCELERATION

IBID197



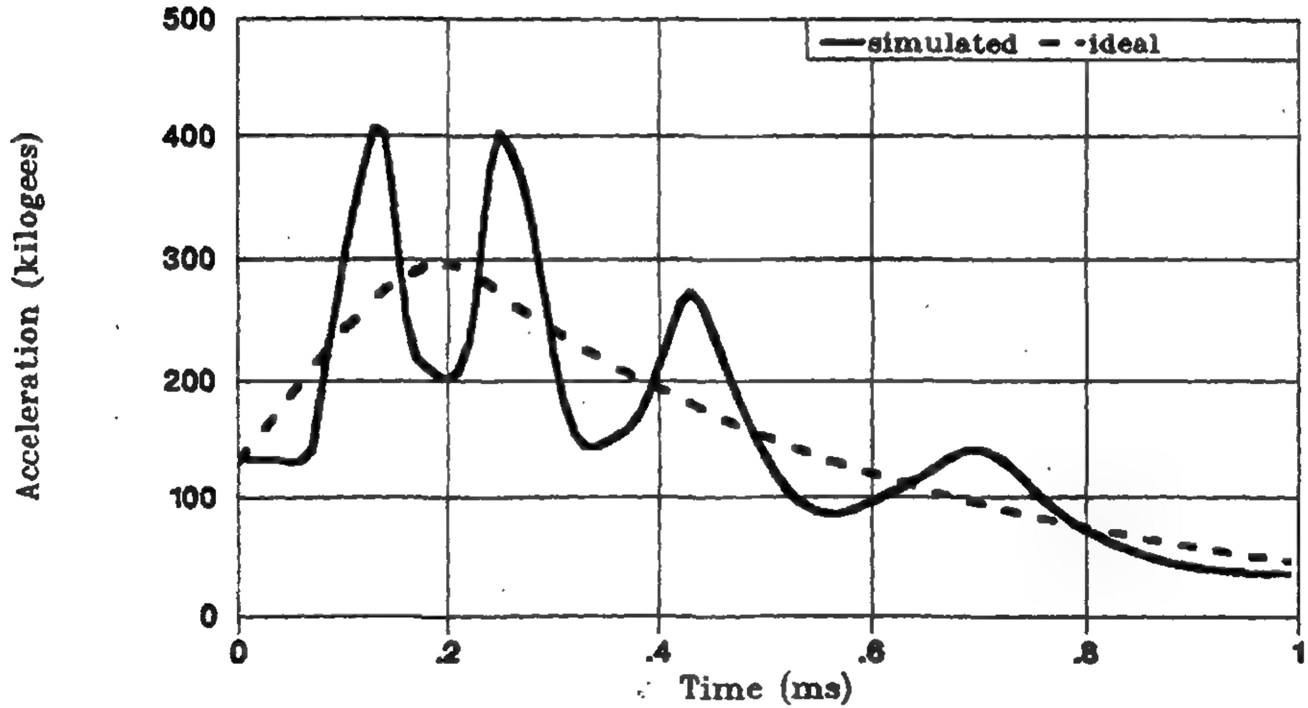
THEORETICAL ARMATURE RESPONSE TO VARIABLE CURRENT

1-Dimensional, Transient Plasma Armature Model

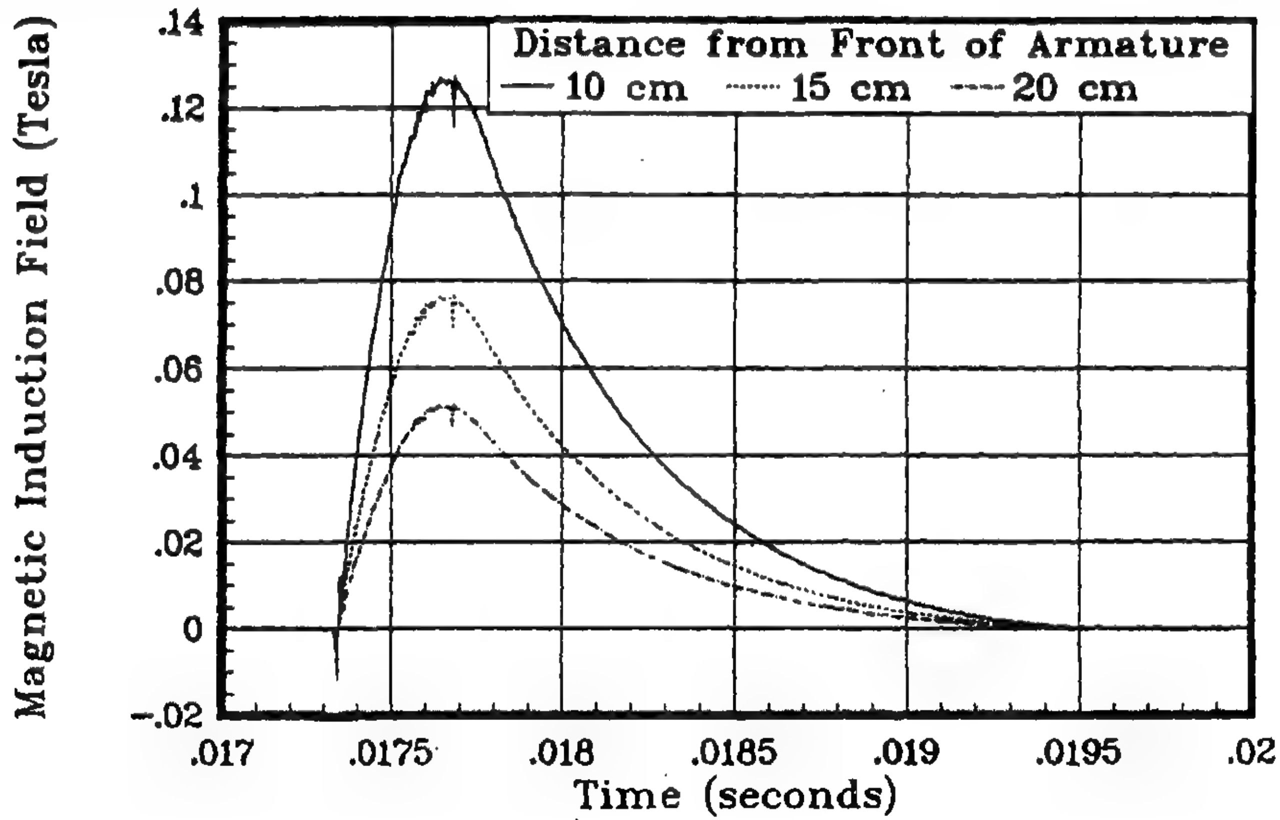


THEORETICAL PROJECTILE ACCELERATION DUE TO VARIABLE CURRENT

1-Dimensional, Transient Plasma Armature Model



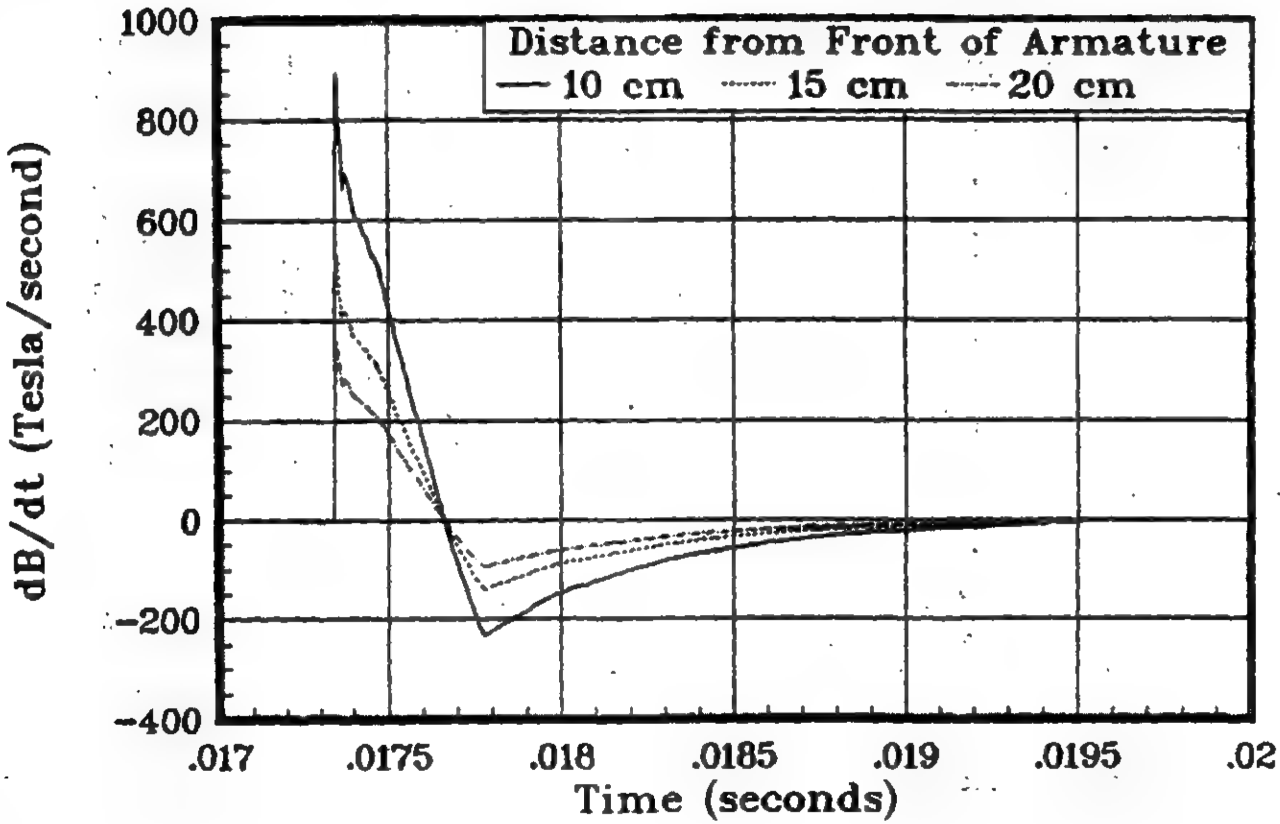
PROJECTILE ENVIRONMENT
CALCULATED MAGNETIC FIELD INTENSITY
IBID235



PROJECTILE ENVIRONMENT

CALCULATED TIME RATE OF CHANGE OF MAGNETIC FIELD INTENSITY

IBID235



CONCLUSIONS

SUMMARY

- TWO GOOD DATA SETS
- AGREEMENT WITH GAS GUN SIMULATION
- AGREEMENT WITH PROBE VELOCITY AND POSITION MEASUREMENTS
- POTENTIAL FOR STUDY OF ARMATURE DYNAMICS

FUTURE PLANS

- NEAR TERM — MEASURE ACCELERATION AT CONSTANT CURRENT
- MID TERM — DEVELOP MORE ADVANCED PAYLOADS WHICH MEASURE OTHER IN-BORE PHENOMENA
- FAR TERM — DEMONSTRATE A HIGHLY INSTRUMENTED PACKAGE TO SIMULTANEOUSLY MEASURE AND RECORD MULTIPLE CRITICAL PARAMETERS RELATING TO SMART PROJECTILES

SUGGESTED READING

D.M. Littrell, K.A. Jamison, R.D. Hudson, M.J. Fernández, and S.A. Ager, "Measurement of Acceleration Using an Instrumented Railgun Projectile," Proceedings of the 3rd European EML Symposium on EML Technology, London England, April 16-18, 1991.

M.J. Fernandez, S.A. Ager, and R.D. Hudson, "In-Bore Instrumentation/Diagnostics for Large-Bore EMLs," IEEE Transactions on Magnetics, 27(1), pp. 185-188, January 1991.

J. Thoman, "Rail Gun Material Survey Summary and Launch Environment Simulator Description," 2nd Electromagnetic Launcher Association meeting, Pomona CA, July 1986.

J. Thompson, "Component Testing and Launch Environment Diagnostics," 3rd Electromagnetic Launcher Association meeting, Tamarron CO, March 1987.

R.G. Grzesik, D.E. Mitchell, J.H. Sebastian, I.W. Chin, and S.A. Kostakis, "E/M Launcher Vibration and Acceleration Data Analysis," IEEE Transactions on Magnetics, 27(1), pp. 147-151, January 1991.

INTENTIONALLY LEFT BLANK.

APPENDIX A:

FINAL AGENDAS

JANNAF Workshop on

Electrothermal-Chemical Modeling and Diagnostics

July 9-11, 1991

Ballistic Research Laboratory
Aberdeen Proving Ground, MD

Workshop Chairman: **Ms. Gloria P. Wren**
Workshop Co-Chairman: **Dr. Arpad A. Juhasz**

A G E N D A

Tuesday, July 9, 1991

8:30	Registration	
8:45	Welcome Administrative Remarks	I. May G. Wren

SESSION I: SERVICE USES OF ETC GUNS & PLASMAS
Chairman: W. Morelli, EAPO

9:00	"National Electric Gun Reviews and Implications for the Army's ETC Gun Technology Program"	W. Oberle
9:30	"Electrothermal Gun Demonstration Program"	C. Dampier
10:15	"Electrothermal (ET) Gun Program"	S. Fowler
10:35	Break	
10:50	"Plasma Discharge in the Electrothermal Gun"	J. Powell
11:15	"Diagnostics and Modeling of an Electrothermal Plasma Source Experiment (SIRENS)"	J. Gilligan O. Hankins
11:40	"Finite Element Analysis of Engineering Electromagnetics of ETC Guns"	R. Boggavarapu
12:05	Lunch	

SESSION II: PROPELLANTS
Chairman: C. Dampier, NSSC

1:15	"Army Atlernate ETC Propellant Program"	D. Downs
1:30	"Overview of Solid Propellant ETC Guns"	A. Juhasz
1:45	"Overview of Gell/Slurry Propellant"	A. Bracuti
2:15	Break	
2:30	"Electrothermal-Chemical (ET-C) Alternate Propellant Systems Investigation and Study Effort"	H. McElroy
3:00	"What's Wrong with Thermochemical Codes Applied to ETC Systems?"	E. Freedman
3:30	"Assessing ETC Performance for Systems Integration"	L. Harris
4:00	Adjourn	

Wednesday, July 10, 1991

SESSION III: MIXING & CONTROL
Chairman: D. Downs, ARDEC

8:00	Administrative Remarks	G. Wren
8:05	"Electrothermal-Chemical Gun Program"	R. Woodfin
8:35	"Diagnostics Development for the ETC Program"	D. Sweeney
9:05	"Development of an Upwind/Implicit Computational Model for the Advancement of Army ETC Guns"	S. Dash
9:40	Break	
9:55	"Recent Advances in CAP_{tm} Gun Modeling"	D. Cook
10:25	"30-MM ETC Ballistic Diagnostic Facility"	K. White
10:45	"Numerical Simulation of the Interior Ballistic Processes in an ETC Gun"	K. Kuo F. Cheung
11:15	Lunch	

SESSION IV: MIXING & CONTROL
Chairman: S. Vosen, SNLL

12:15	"Finite-Element Modeling of Electrothermal-Chemical Guns"	N. Winsor
12:45	"Special Diagnostics and Instrumentation"	R. Richardson
1:15	Break	
1:30	"First Principles Modeling of a DNA 60mm ETC Gun Design"	CC. Hsiao
2:00	"Physics of ETC Plasma-Fluid Interactions"	B. Kashiwa
2:30	"Observations and Modeling of Fundamental Electrothermal Gun Phenomena"	H. Davis
3:00	Adjourn	
4:00	Bus leaves from Sheraton Inn to the Inner Harbor	

Thursday, July 11, 1991

SESSION V: LESSONS LEARNED FROM OTHER FIELDS
Chairman: J. Gilligan, NC State U.

8:00	"Electrothermal-Chemical Gun Modeling"	D. King
8:30	"Railgun Research Relevant to Electrothermal Guns"	J. Batteh
9:00	"In-Bore Position and Velocity Measurement Techniques"	R. Bartsch
9:30	Break	
9:45	"In-Bore Acceleration Measurements with an Instrumented Railgun Projectile"	D. Littrell
10:15	Group Discussion and Wrap-up	G. Wren
12:00	Adjourn	

APPENDIX B:

ATTENDEES

INTENTIONALLY LEFT BLANK.

JANNAF Workshop on
Electrothermal-Chemical Modeling and Diagnostics

July 9-11, 1991

Attendees

Dr. Robert Armstrong
Sandia National Laboratories
Energetic Materials Division, 8357
Combustion Research Facility
Livermore, CA 94551-0969
(415) 294-2470

Dr. Jad Batteh
Science Applications Int'l Corp.
1519 Johnson Ferry Road, Suite 300
Marietta, GA 30068
(404) 973-8935

Dr. R. Richard Bartsch
Los Alamos National Laboratory
Mail Stop E526 (Group P-1)
Los Alamos, NM 87545
(505) 667-9977

Dr. Rao L. Boggavarapu
General Dynamics Land Systems
Division
PO Box 2074
Warren, MI 48090-2074
(313) 825-5350

Dr. Mohamed Bourham
Department of Nuclear Engineering
Box 7909
North Carolina State University
Raleigh, NC 27695
(919) 737-7662

Dr. Arthur Bracuti
US Army Armament Research, and
Development & Engineering Center
ATTN: SMCAR-AEE
Picatinny Arsenal, NJ 07806-5000
(201) 724-5759

Mr. Henry Burden
Ballistic Research Laboratory
ATTN: SLCBR-TB
Aberdeen Proving Ground, MD
21005-5066
(301) 278-4363

Mr. Donald Chiu
US Army Armament Research, and
Development & Engineering Center
ATTN: SMCAR-AEE
Picatinny Arsenal, NJ 07806-5000
(201) 724-5759

Dr. David Cook
FMC Corporation
Naval Systems Division - M170
4800 E. River Road
Minneapolis, MN 55421-1498
(612) 572-4744

CDR Craig Dampier
Naval Sea Systems Command
Dept. of the Navy
CSEA 06 KR12
Washington, DC 20362-5101
(703) 602-2941

Dr. Sanford Dash
Science Applications Int'l Corp.
501 Office Center Drive
Suite 420
Ft. Washington, PA 19034-3211
(215) 542-1200

Dr. Harold Davis
Los Alamos National Laboratory
P-1, MS E526
Los Alamos, NM 87545
(505) 667-8373

Mr. James DeSpirito
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6104

Mr. Thomas E. Doran
Code G33
Naval Surface Warfare Center
Dalgren, VA 22448-5000
(703) 663-8188

Dr. David S. Downs
US Army Armament Research, and
Development and Engineering Center
ATTN: SMCAR-AEE-B, Bldg 382
Picatinny Arsenal, NJ 07806-5000
(201) 724-2219

Mr. Jahn Dyvik
FMC Corporation
Naval Systems Division - M170
4800 E. River Road
Minneapolis, MN 55421-1498
(612) 572-4756

Mr. Stuart Fowler
Laser Radar Branch
Optical Systems Dept.
Teledyne Brown Engineering
Cummings Research Park
300 Sparkman Drive, NW
PO Box 070007 / MS 19
Huntsville, AL 35807-7007
(205) 726-2576

Dr. Eli Freedman
Eli Freedman & Associates
2411 Diana Road
Baltimore, MD 21209-1525
(301) 484-0632

Dr. John Gilligan
North Carolina State University
Department of Nuclear Engineering
Box 7909
Raleigh, NC 27695
(919) 737-2301

Dr. Paul S. Gough
Paul Gough Associates, Inc.
1048 South Street
Portsmouth, NH 03801
(603) 436-5172

Dr. J. Robert Greig
GT-Devices, Inc.
5705A General Washington Drive
Alexandria, VA 22312
(703) 642-8150

Dr. Orlando Hankins
Department of Nuclear Engineering
Box 7909
North Carolina State University
Raleigh, NC 27695
(919) 737-2301

Dr. Lee E. Harris
US Army Armament Research, and
Development and Engineering Center
ATTN: SMCAR-AEE-BR, Bldg 382
Picatinny Arsenal, NJ 07806-5000
(201) 724-4535

Dr. Ashwin Hosangadi
Science Applications Int'l Corp.
501 Office Center Drive
Suite 420
Fort Washington, PA 19034-3211
(215) 542-1200

Mr. CC. Hsiao
Science Applications Int'l Corp.
10210 Campus Point Drive
San Diego, CA 92121
(619) 458-5058

Dr. Arpad A. Juhasz
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6158

Mr. Gary Katulka
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6184

Dr. Dennis Keefer
University of Tennessee Space
Institute
Center for Laser Applications, MS-14
Tullahoma, TN 37388-8897
(615) 455-0631

Mr. John Knapton
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6170

CPT Kevin Nekula
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6856

Professor Kenneth K. Kuo
The Pennsylvania State University
Propulsion Engr Rsch Ctr/Mech Engr
Dept
140 Research Building "E"
University Park, PA 16802
(814) 863-6270

Mr. Donald M. Littrell
WL/MNSH
Electromagnetic Launcher Tech Branch
Hypervelocity Research Complex
Wright Laboratory//Armament
Directorate
Eglin Air Force Base, FL 32542-5434
(904) 882-0395

Dr. John Mandzy
Defense Systems Division
General Electric Company
100 Plastics Avenue
Pittsfield, MA 01201
(413) 494-5333

Dr. Ingo May
Ballistic Research Laboratory
ATTN: SLCBR-IB
APG, MD. 21005-5066
(301) 278-6093

Mr. Hugh A. McElroy
Olin Ordnance
10101 9th Street North
St. Petersburg, FL 33716
(813) 578-8239

Dr. Neale Messina
Princeton Combustion Rsch Lab
4275 US Highway One North
Monmouth Junction, NJ 08852
(609) 452-9200

Mr. William Morelli
US Army Armament Research, and
Development & Engineering Center
Electric Armaments Program Office
(EAPO)
ATTN: SMCAR-FSC, Bldg 329 Annex
Fire Support Armaments Center
Picatinny Arsenal, NJ 07806-5000
(201) 724-6612

Dr. Walter F. Morrison
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6189

Mr. William Oberle
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6200

Dr. Gary Phillips
Science Applications Int'l Corp.
10210 Campus Point Drive
San Diego, CA 92121
(619) 546-6603

Dr. John D. Powell
Ballistic Research Laboratory
ATTN: SLCBR-TB-E
Aberdeen Proving Ground, MD
21005-5066
(301) 278-5783

Dr. Rex D. Richardson
Science Applications Int;l Corp.
2109 Air Park Road, SE
Albuquerque, NM 87106
(505) 247-8787

Mr. Todd Rosenburger
Ballistic Research Laboratory
ATTN: SLCBR-IB-A
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6136

Dr. W. J. Sarjeant
Professor, State University of New
York
at Buffalo
Department of Electrical Engineering
312 Bonner ECE-SUNY/AB
Buffalo, NY 14260
(716) 636-3117
Also----
W.J. Schafer Associates
(703) 558-7900

Dr. Donald W. Sweeney
Sandia National Laboratories
Combustion Research Facility,
Org. 8351
PO Box 969
Livermore, CA 94550
(415) 294-3138

Mr. Lindsey Thornhill
Science Applications Int'l Corp.
1519 Johnson Ferry Road, Suite 300
Marietta, GA 30062
(404) 973-8935

Mr. David Toepler
General Dynamics Land Systems
Division
MZ 436-21-19
PO Box 2074
Warren, MI 48090-2074
(313) 825-5273

Dr. R. James Trainor
Los Alamos National Laboratory
Group P-1, MS E526
Los Alamos, NM 87545
(505) 667-4879

Ms. Phuong Tran
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6199

Dr. Steven Vosen
Sandia National Laboratories
Division 8357
Livermore, CA 94551-0969
(415) 294-3434

Dr. Eduardo Waisman
S-Cubed Division of Maxwell Labs
3398 Carmel Mountain Road
San Diego, CA 92121
(619) 587-8486

Dr. Kevin White
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6184

Dr. Melvin Widner
General Dynamics Land Systems
Division
Mail Zone 436-21-14
PO Box 2074
Warren, MI 48090-2074
(313) 825-5072

Mr. G. Mark Wilkinson
Maxwell Laboratories
8888 Balboa Avenue
San Diego, CA 92123
(619) 576-7589

Dr. Neils K. Winsor
GT-Devices, Inc.
5705A General Washington Drive
Alexandria, VA 22312
(703) 642-8150

Dr. Ronald L. Woodfin
Sandia National Laboratories
Advanced Projects Division V,
Org. 9128
Albuquerque, NM 87185-5800
(505) 844-3111

Ms. Gloria P. Wren
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6199

Mr. Alex Zielinski
Ballistic Research Laboratory
ATTN: SLCBR-TB
Aberdeen Proving Ground, MD
21005-5066
(301) 278-3883

No. of Copies	Organization
2	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145
1	Commander U.S. Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Commander U.S. Army Laboratory Command ATTN: AMSLC-DL 2800 Powder Mill Road Adelphi, MD 20783-1145
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-IMI-I Picatinny Arsenal, NJ 07806-5000
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-TDC Picatinny Arsenal, NJ 07806-5000
1	Director Benet Weapons Laboratory U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050
(Unclass. only)1	Commander U.S. Army Armament, Munitions and Chemical Command ATTN: AMSMC-IMF-L Rock Island, IL 61299-5000
1	Director U.S. Army Aviation Research and Technology Activity ATTN: SAVRT-R (Library) M/S 219-3 Ames Research Center Moffett Field, CA 94035-1000
1	Commander U.S. Army Missile Command ATTN: AMSMI-RD-CS-R (DOC) Redstone Arsenal, AL 35898-5010
1	Commander U.S. Army Tank-Automotive Command ATTN: ASQNC-TAC-DIT (Technical Information Center) Warren, MI 48397-5000
1	Director U.S. Army TRADOC Analysis Command ATTN: ATRC-WSR White Sands Missile Range, NM 88002-5502
1	Commandant U.S. Army Field Artillery School ATTN: ATSF-CSI Ft. Sill, OK 73503-5000
(Class. only)1	Commandant U.S. Army Infantry School ATTN: ATSH-CD (Security Mgr.) Fort Benning, GA 31905-5660
(Unclass. only)1	Commandant U.S. Army Infantry School ATTN: ATSH-CD-CSO-OR Fort Benning, GA 31905-5660
1	Air Force Armament Laboratory ATTN: WL/MNOI Eglin AFB, FL 32542-5000

<u>Aberdeen Proving Ground</u>

No. of Copies	Organization
2	Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen
1	Cdr, USATECOM ATTN: AMSTE-TC
3	Cdr, CRDEC, AMCCOM ATTN: SMCCR-RSP-A SMCCR-MU SMCCR-MSI
1	Dir, VLAMO ATTN: AMSLC-VL-D
10	Dir, BRL ATTN: SLCBR-DD-T

No. of Copies	Organization
2	Defense Nuclear Agency ATTN: John Farber Dr. R. Rohr 6801 Telegraph Road Alexandria, VA 22310
2	ODDR&E/R&AT ATTN: John Appel R. Mentz Pentagon, Room 3D1089 Washington, DC 20301-3080
1	U.S. Army Armament Research, and Development and Engineering Center ATTN: SMCAR-AEE, Arthur Bracuti Picatinny Arsenal, NJ 07806-5000
3	U.S. Army Armament Research, and Development and Engineering Center ATTN: SMCAR-AEE-B, Bldg. 382 Dr. Anthony Beardell Donald Chiu Dr. David Downs Picatinny Arsenal, NJ 07806-5000
1	U.S. Army Armament Research, and Development and Engineering Center ATTN: SMCAR-AEE-BR, Bldg. 382 Dr. Lee Harris Picatinny Arsenal, NJ 07806-5000
3	U.S. Army Armament Research, and Development and Engineering Center Electric Armaments Program Office (EAPO) ATTN: SMCAR-FSC, Bldg. 329 Annex Gregory Ferdinand MAJ R. Lunberg William Morelli Fire Support Armaments Center Picatinny Arsenal, NJ 07806-5000
1	U.S. Army Armament Research, and Development and Engineering Center ATTN: SMCAR-FSC, Hildi Libby Picatinny Arsenal, NJ 07806-5000
1	Army Research Office ATTN: Dr. David Mann P.O. Box 12211 Research Triangle Park, NC 27709

No. of Copies	Organization
1	Department of the Navy Naval Sea Systems Command ATTN: CDR Craig Dampier CSEA 06 KR12 Washington, DC 20362-5101
1	Naval Surface Warfare Center ATTN: Thomas Doran Code G33 Dalgren, VA 22448-5000
1	WL/MNSH Electromagnetic Launcher Technology Branch ATTN: Donald M. Littrell Hypervelocity Research Complex Wright Laboratory/Armament Directorate Eglin Air Force Base, FL 32542-5434
1	WL/MNSH ATTN: Al Young Eglin Air Force Base, FL 32542-5434
3	Los Alamos National Laboratory ATTN: Dr. R. Richard Bartsch Dr. Harold Davis Dr. James Trainor Group P-1, MS E526 Los Alamos, NM 87545
1	Los Alamos National Laboratory ATTN: Dr. Bryan Kashiwa Fluid Dynamics Group, MS B216 Los Alamos, NM 87545
1	Sandia National Laboratories Advanced Projects Division, Org. 9123 ATTN: Dr. David Benson Albuquerque, NM 87185-5800
1	Sandia National Laboratories Division 1811 ATTN: Dr. Paul Cahill Albuquerque, NM 87185-5800
1	Sandia National Laboratories Advanced Projects V ATTN: Dr. Steve Kempka Albuquerque, NM 87185-5800

No. of Copies	Organization
1	Sandia National Laboratories Advanced Projects Division V, Org. 9128 ATTN: Dr. Ronald L. Woodfin Albuquerque, NM 87185-5800
1	Sandia National Laboratories ATTN: Dr. Thomas Hitchcock Albuquerque, NM 87185-5800
1	Sandia National Laboratories Energetic Materials Division, Org. 8357 Combustion Research Facility ATTN: Dr. Robert Armstrong Livermore, CA 94551-0969
1	Sandia National Laboratories Combustion Research Facility, Org. 8351 ATTN: Dr. Donald W. Sweeney P.O. Box 969 Livermore, CA 94550
1	Sandia National Laboratories Division 8357 ATTN: Dr. Steven Vosen Livermore, CA 94551-0969
1	Maxwell Laboratories, Inc. ATTN: Ian R. McNab VP, Kinetic-Energy Technologies 8888 Balboa Avenue San Diego, CA 92123
1	Maxwell Laboratories, Inc. ATTN: G. Mark Wilkinson 8888 Balboa Avenue San Diego, CA 92123
1	S-Cubed Division of Maxwell Labs ATTN: Eduardo Waisman 3398 Carmel Mountain Road San Diego, CA 92121
1	Princeton Combustion Research Laboratory ATTN: Dr. Neale Messina 4275 U.S. Highway One North Monmouth Junction, NJ 08852

No. of Copies	Organization
1	Olin Rocket Research ATTN: Dr. David Q. King 11441 Willows Road, N.E. Redmond, WA 98073
2	The Pennsylvania State University Propulsion Engineering Research Center Mechanical Engineering Department ATTN: Professor F. B. Cheung Professor Kenneth K. Kuo 140 Research Building "E" University Park, PA 16802
3	North Carolina State University Department of Nuclear Engineering ATTN: Dr. Mohomed Bourham Dr. John Gilligan Dr. Orlando Hankins Box 7909 Raleigh, NC 27695-7909
1	State University of New York at Buffalo Department of Electrical Engineering ATTN: Professor Dr. W. J. Sarjeant 312 Bonner ECE-SUNY/AB Buffalo, NY 14260
1	University of Tennessee Space Institute ATTN: Dr. Dennis R. Keefer Center for Laser Applications, MS-14 Tullahoma, TN 37388-8897
1	FMC Corporation Naval Systems Division - M170 ATTN: Dr. David Cook 4800 East River Road Minneapolis, MN 55421-1498
3	FMC Corporation Northern Ordnance Division - M170 ATTN: Dr. Anthony Giovanetti Dr. Gene Johnson Jahn Dyvik 4800 East River Road Minneapolis, MN 55421-1498

No. of Copies	Organization
2	General Dynamics Land Systems Division ATTN: D. Rao L. Boggavarapu P.O. Box 2074 Warren, MI 48090-2074
1	General Dynamics Land Systems Division ATTN: Dr. Melvin Widner MZ 436-21-14 P.O. Box 2074 Warren, MI 48090-2074
1	General Dynamics Land Systems Division ATTN: Dave Toepler MZ 436-21-19 P.O. Box 2074 Warren, MI 48090-2074
1	General Electric Defense Systems Department ATTN: Dr. John Mandzy Bldg. 43-220 100 Plastics Avenue Pittsfield, MA 01201
3	GT-Devices, Inc. ATTN: Dr. J. Robert Greig Dr. Derek Tidman Dr. Neils Winsor 5705A General Washington Drive Alexandria, VA 22312
1	Olin Ordnance ATTN: Hugh A. McElroy 10101 9th Street North St. Petersburg, FL 33716
2	Science Applications International Corp. ATTN: Dr. Jad Batteh Lindsey Thornhill 1519 Johnson Ferry Road, Suite 300 Marietta, GA 30068
3	Science Applications International Corp. ATTN: Dr. Sanford Dash Dr. Ashwin Hosangadi Neeraj Sinha 501 Office Center Drive, Suite 420 Fort Washington, PA 19034-3211
2	Science Applications International Corp. ATTN: C. C. Hsiao Dr. Gary Phillips 10210 Campus Point Drive San Diego, CA 92121
1	Science Applications International Corp. ATTN: Dr. Rex D. Richardson 2109 Air Park Road, SE Albuquerque, NM 87106
1	Teledyne Brown Engineering ATTN: Stuart Fowler P.O. Box 070007, MS 19 Huntsville, AL 35807-7007
1	Eli Freedman and Associates ATTN: Dr. Eli Freedman 2411 Diana Road Baltimore, MD 21209
1	Paul Gough Associates, Inc. ATTN: Dr. Paul S. Gough 1048 South Street Portsmouth, NH 03801
1	Dr. Keith Jamison P.O. Box 1261 Shalimar, FL 32579
1	Dr. Bruce van Duesen General Dynamics Land Systems Division P.O. Box 2074 Warren, MI 48090-2074

*U.S. GOVERNMENT PRINTING OFFICE: 1992 -311-851/60007

USER EVALUATION SHEET/CHANGE OF ADDRESS

This laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers below will aid us in our efforts.

1. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ______________________________

2. How, specifically, is the report being used? (Information source, design data, procedure, source of ideas, etc.) ______________________________

3. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______________________________

4. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ______________________________

BRL Report Number BRL-SP-92 Division Symbol __________

Check here if desire to be removed from distribution list. ____

Check here for address change. ____

Current address: Organization ______________________

Address ______________________

DEPARTMENT OF THE ARMY
Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

OFFICIAL BUSINESS

NO POSTAGE NECESSARY IF MAILED IN THE UNITED STATES

BUSINESS REPLY MAIL
FIRST CLASS PERMIT No 0001, APG, MD

Postage will be paid by addressee.

Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066